Universidade de Aveiro Departamento de Engenharia Mecânica
2019

Daniel Canosa Santos

Desenvolvimento de um novo suporte para avião: otimização topológica para fabrico aditivo

Development of a new aircraft bracket: topology optimization for additive manufacturing

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica de Carlos Alberto Moura Relvas, Professor auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

Esta dissertação teve o apoio dos projetos UID/EMS/00481/2019-FCT - FCT - Fundação para a Ciência e a Tecnologia e CENTRO-01-0145-FEDER-022083 - Programa Operacional Regional do Centro (Centro2020), através do Portugal 2020 e do Fundo Europeu de Desenvolvimento Regional.

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Agradecimentos/ Acknowledgements

Ao Professor Carlos Relvas por ter aceitado orientar a dissertação, pela sua disponibilidade e ajuda.

Ao Tayfun Süle, responsável do estágio na empresa, pelo apoio dado ao longo destes meses, integração e partilha da sua experiência.

Ao Volker Galla pela disponibilidade e apoio.

À Daniela e Tom Heinkel pela oportunidade e boa disposição.

Ao Kenneth pela sua experiência e ajuda nos ajustes técnicos dos equipamentos.

À equipa e restantes colegas da empresa pela partilha de experiência e apoio prestado em Finkenwerder (Em especial ao Dima Biryukov).

Ao Danilo Loaiza, Suren e Susanna Amirkhanyan pela amizade.

Aos meus amigos pela cumplicidade e apoio.

Com muito carinho aos meus pais, Arlindo e Rosa, à minha irmã Alexandra e restante família pelo apoio incansável e compreensão.

À Aigul pela força e motivação.

Aos meus avós.

Palavras-chave

Fabrico aditivo, impressão 3D, otimização topológica, modelação, desenho, produção, peso, suporte, cabine, avião

Resumo

A dissertação descreve o trabalho desenvolvido entre setembro e fevereiro de 2019 na empresa Heinkel Group em Hamburgo, Alemanha. Este ocorreu no âmbito da unidade curricular "Dissertação/Projeto/Estágio do segundo semestre do quinto ano do Mestrado Integrado em Engenharia Mecânica da Universidade de Aveiro. O estágio teve como principal tarefa a otimização de um suporte usado no Airbus A380, no qual é fabricado por métodos convencionais e redesenhá-lo de forma a ser aplicável para fabrico aditivo (FA). O primeiro passo foi realizar análises estruturais ao suporte original para poder comparar os resultados com as soluções desenvolvidas. Várias otimizações topológicas foram depois utilizadas para averiguar quais os volumes do modelo poderiam ser eliminados e diferentes conceitos foram elaborados. O principal objetivo deste projeto foi a exploração do uso do fabrico aditivo para desenvolver um suporte mais leve, mas tão eficaz como aquele usado no avião. O trabalho é também um estudo das vantagens da tecnologia na área aerospacial, que traz um grande potencial no desenvolvimento de estruturas leves que são determinantes, por exemplo, para reduzir o consumo de combustível do avião e por consequência o seu impacto ambiental. O objetivo principal do estágio foi desenvolver aptidões na conceção e construção de componentes usando fabrico aditivo, explorando as suas vantagens e aprendendo a desenhar para FA. Mesmo que a tecnologia permita uma grande liberdade no desenho, a produtibilidade requer o uso das melhores práticas durante a conceção do produto.

Keywords

Additive manufacturing, 3D Printing, topology optimization, modeling design, production, weight, support, cabin, aircraft

Abstract

The dissertation describes the work done between September and February 2019 at Heinkel Group in Hamburg, Germany. This work was made in context of the subject “Dissertation/Project/Internship” of the second semester of the fifth year of the Integrated Master’s Degree in Mechanical Engineering of the University of Aveiro. The main task of this internship was to optimize an original bracket used in the Airbus A380 which is manufactured by conventional methods and to redesign it in a way to be suitable for additive manufacturing (AM). A first step was to perform the structural analyses of the original part in order to compare the results with the solutions created. Several topology optimizations where made to determine which volumes could be removed from the original bracket and several concepts were developed. The main goal of this project was to explore the use of additive manufacturing to create a lighter bracket but as performant as the one used in the aircraft. This work is also an exploration of the advantages of the technology in an area such as aerospace, bringing a big potential in the development of lightweight structures that are determining, for example, to reduce the fuel consumption of the aircraft and therefore its environmental impact. The main goal of this internship was to get in touch with the potentials of the technology of additive manufacturing, exploring its advantages and learning on how to design for AM. Even though the technology allows a high design freedom, the manufacturability requires the use of best practices while designing the product.

Contents

List of Figures

List of Tables

1. Introduction

1.1 Contextualization

My interest in additive manufacturing was consistent in the last years of the Mechanical Engineering degree especially when I saw organizations manufacturing products with designs inspired by nature or with complex and innovative shapes. In addition, the aerospace was also an area that I had interest by the fact to be an innovative field that is always one step ahead in the future. Having investigated the companies that could bring these two possibilities together, in other words, to develop my work in a project related with additive manufacturing and aerospace I found an open door at Heinkel Group.

Heinkel Group is a consulting firm that provides professional expertise in different technology sectors. The department where the internship occurred, Heinkel Engineering, provide outsourcing in different areas such as acoustics, cabin stress solutions, additive manufacturing, structure calculation and testing. One of the offices is in Finkenwerder (Southwest of Hamburg, Germany) that is next to the plant of Airbus and its private airport. There is a high demand of services, many project's assignments and Airbus choose to delegate to nearby companies and one of them is Heinkel Group.

Bionic Studio is a division represented at Heinkel Engineering that works with the development of products using additive manufacturing. The responsible of this sub department, also the company's supervisor of my work, gave as a suggestion to develop a new aircraft bracket adapted to be manufactured with additive manufacturing, being this work the main task of the internship.

1.2 Objective

The work made in the context of the internship focused on the development of solutions for additive manufacturing, applying the right tools and methods for each case. The main objective of this work is to redesign an existent bracket used in the Airbus A380 that is attached to the fuselage that holds different components above the cabin. At first it is necessary to run structural simulations with the original bracket in order to compare with the posterior results of the developed brackets. It is intended to do a topology optimization to develop a new solution that is lighter and as mechanical performant as the one that is originally used. The design of the new bracket must be suitable to be manufactured with additive manufacturing technologies. Another of the objectives was also to get acquainted with the softwares, especially Autodesk Fusion 360 and also to improve 3D-construction knowledge. The application of the gathered knowledge by developing the main task will help to have a better understanding of the potentials and limitations of additive manufacturing.

1.3 Organization

This document is divided in four chapters. The first one describes the contextualization and objectives of the work. The second chapter contains a review of topics about additive manufacturing and ends with the contribution of the dissertation. The third chapter reports the procedures taken to develop the main task of the internship and show all the analyses and results obtained to develop the final solution. It also documents the validation of the concept. The fourth and last chapter concludes the dissertation and review the overall outputs of the internship. Annexed to the dissertation can be found relevant documentation produced in the context of the work.

2. Bibliographic Review

2.1 Product development using rapid prototyping processes

Product Development process is the set of activities that starts with the perception of a market opportunity and finish with the production, sale, and delivery of a product (1). We can also define it as a combination of many efforts towards the creation of a product that can be produced and sold profitably.

The management of complex product development processes and its research has led to many innovations and improvements with the automobile, electronics, aerospace, medical devices and equipment industries as an example.

As an interdisciplinary activity it requires many professionals in different areas from the marketing area, the design and manufacturing and many activities requires different individuals with different type of knowledge to add a specific value into the product. The composition of these people creates a team that work together effectively in the development of the product. Following the logic created by Ulrich and Eppinger, the product development process can be divided into 6 phases (1):

Phase 0- Planning: includes the first tasks of significant importance to discover the available technologies and to define different market opportunities;
Phase 1- Concept Development: investigate the customer needs and develop industrial design concepts;
Phase 2- System-Level Design: identify suppliers for key components and define the final assembly scheme;
Phase 3- Detail Design: define the parts geometries, choose materials and define quality assurance processes;
Phase 4- Testing and Refinement: implement design changes and obtain regulatory approvals;

Phase 5- Production Ramp-up: place early production with key customers and begin full operation of production system.

The figure 2.1 illustrates the main stages from development until production (1).

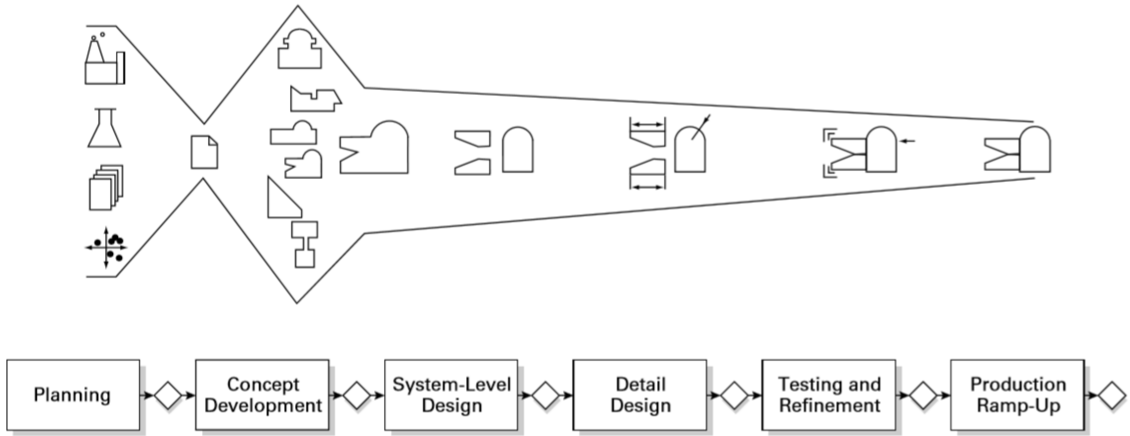


Figure 2.1 Main stages of product development (1)

Depending on the characteristics of the product the developing time will vary. The table 2.1 shows the developing time for 3 different products.

Table 2.1 Developing time of three products

	HP Desk Jet Printer 	Volkswagen Beetle 	Boeing 777 Airplane 
Developing time (1)	1.5 years	3.5 years	4.5 years

Rapid Prototyping

Rapid Prototyping (RP) is been used in product development to help organizations in taking better choices. It is a tool of communication that has been used to estimate future changes and to provide essential information as form of feedback to help engineers and designers. Rapid prototyping is the combination of technologies used to develop physical components from 3D models, created by means of computer-aided design or 3D scanning. The first time that Rapid Prototyping was used was in the early 1980s. The main goal of using Rapid Prototyping in the product development is to reduce design and manufacturing costs and leads times to increase competitiveness (2). It is considered very useful when presenting the idea to the potential customers and to collect opinions and details that are very important during the early stages of product development.

Different authors defend a different way of thinking about prototypes and they conceptualize them as filters (3), defending that the most efficient prototype is the most incomplete one that filters the qualities that the engineer or designer wants to examine and explore (Figure 2.2). They argue that a design space is extremely large and complex, therefore it is not feasible to explore the whole space at one time.

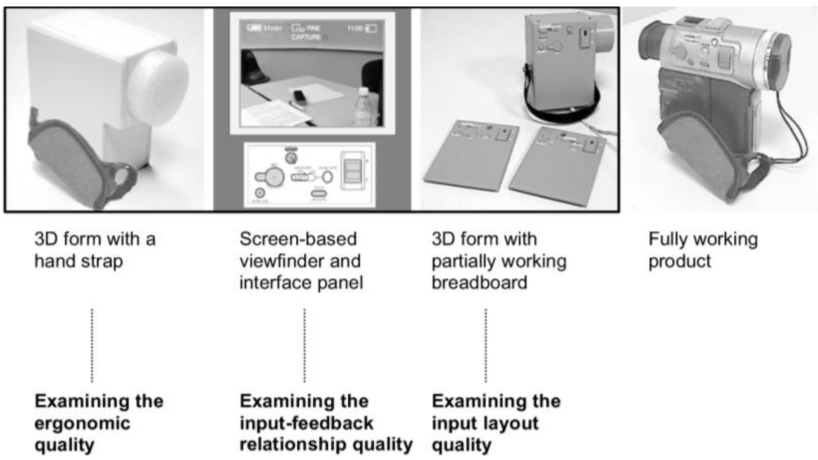


Figure 2.2 Product development using prototypes as filters (3)

Following the classification of Pham et al the main RP technologies can be divided in two big groups: some of them are based on material addition and the others in material removal like CNC machining (4). The second stage that divides these two initial groups is influenced by the state of the material before forming the part. The materials can be liquid or solid.

The Figure 2.3 illustrates the classification as defined by Pham et al. (4)

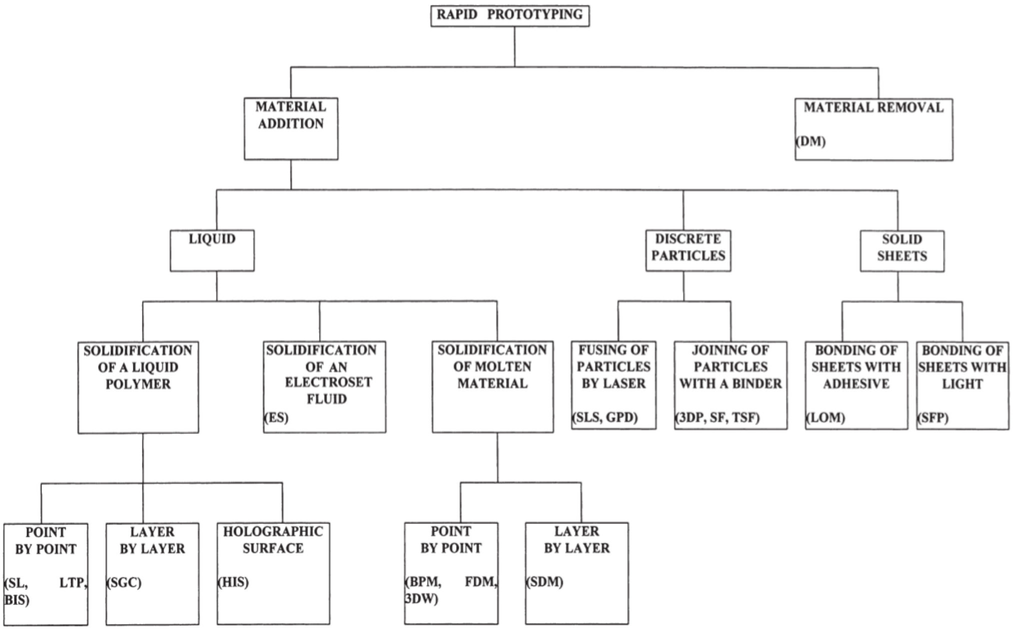


Figure 2.3 Classification of rapid prototyping technologies (4)

2.2 From rapid prototyping to additive manufacturing

Additive manufacturing (AM) is a development from rapid prototyping and aims to produce end-use parts rather than prototypes. It separates the processes of rapid prototyping that build 3D objects by adding layer-upon-layer of material and enables organizations and companies to achieve new levels of performance with their products.

The term '3D Printing' is been used by a much wider audience due to the spread from the media about the technology and the fact that more 3D printers are available in the consumer market nowadays. Even so, the term additive manufacturing is still the term commonly used by advanced professionals and the industry.

The high degree of complexity that is usually undesired due to the limitations of traditional manufacturing can be seen in a different way with additive manufacturing and bring innovation.

The four main material categories for additive manufacturing applications are polymers, metals, ceramics and composites. (Figure 2.4)

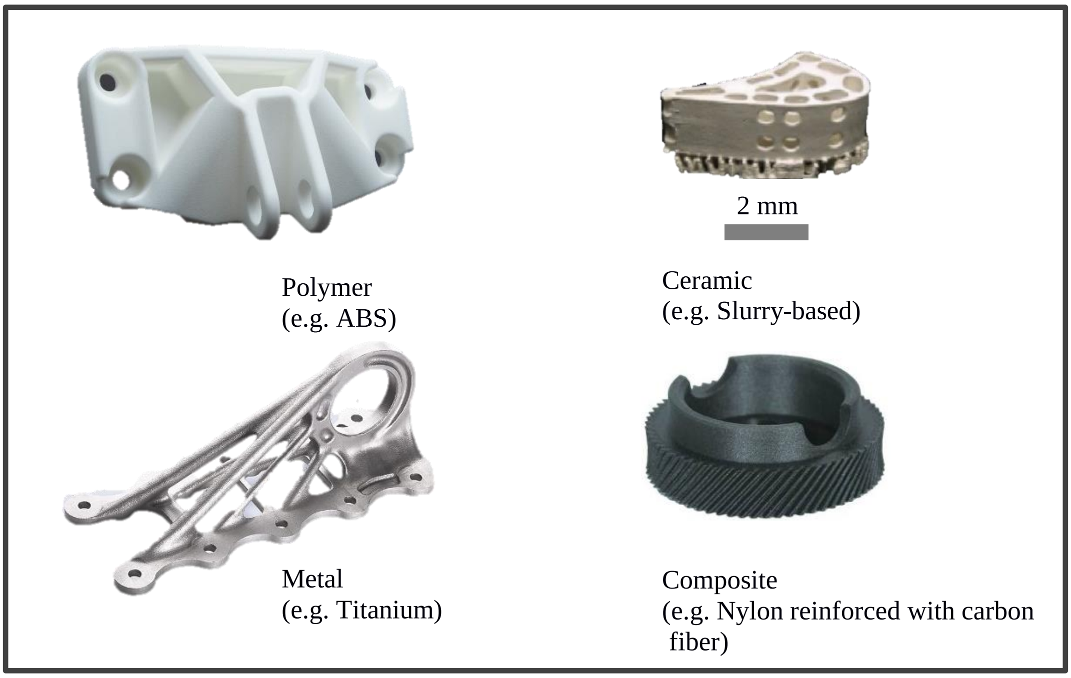


Figure 2.4 The main AM material categories

2.2.1 Examples of applications with additive manufacturing

Some cases and implementing jobs of additive manufacturing were selected in order to enhance its most important characteristics and applications.

Maintenance/Repairs

Additive manufacturing has been proved to be an effective in-situ repair technology for different industries. Military aircraft is one field that the AM-based technologies have been well explored where organizations use it for geometric restoration and structural repair.
The Israeli Air Force's Aerial Maintenance Unit (AMU) is using additive manufacturing to upgrade their aircraft equipment and instead of using large financial resources to acquire new aircraft and components, the AMU is using their equipment and personal to substitute damaged and outdated aircraft (5). In the case of their F-15 aircrafts they are also using 3D scanning technology to produce their replacement parts with polymer materials and aims to use titanium.

Lightweight components

Additive manufacturing holds a great potential for improving the design of parts that already exist to achieve energy and emissions savings. Especially with aerospace and automotive industry some redesigned components for AM are already in use. The companies and organizations involved are making efforts so that the regulatory stakeholders develop new and more technical standards that will support the certification of AM parts (6).

The first 3D printed metal component used in a production series vehicle was used in the 2018 BMW i8 Roadster (Figure 2.5). The bracket is used in its convertible roof. The additive manufacturing technology used into a series production was able to reduce the weight of the part on 44% (7). As early as 1990, the BMW Group has started to use additive manufacturing methods in different product development researches.

Figure 2.5 Several thousand brackets were printed for the BMW i8 Roadster (7)

Transformational Productivity

The company Sandvik Coromant has created an optimal cutter design with AM to substitute its conventional tool. The features of the new tool, that are impossible to replicate with traditional machining processes, allows the tool to have its productivity increased by 200%. The tool is needed in deep cavities with long overhangs and the vibration must be minimized in order to have better results. The complex structure allows to reduce the vibration and increased its material removal rate from 30.5cm^3/min to 45.8cm^3/min. The weight was also reduced to more than 80% and the lead time was reduced compared to its conventional cutter (8).

Conventional Manufacturing
$Q = 30.5cm^3/min$

Additive Manufacturing
$Q = 45.8cm^3/min$

Figure 2.6 Significant changes in productivity for the metal cutter (8)

Cooling passages/air recirculation

Siemens reports to have successfully tested their AM turbine blades made of polycrystalline nickel superalloy in an industrial turbine gas engine with a capacity of 13MW. The full-load tests achieved promising results showing that the additive blades endured 13 000 revolutions per minute surrounded by gas at 1250^o. The advanced features in this gas turbine are the internal and external cooling schemes. These complex features reduce cooling flow requirements by more than 15% and increase the overall efficiency of the gas turbines. The improved design was able to elevate the fuel efficiency of the gas turbine (9).

Figure 2.7 Cooling channels in AM turbine blade (9)

Customization

An example of the importance of custom products is the prosthetic field. Each prosthetic limb must be custom designed and manufactured to fit the patient's body. If it is designed for children, the need to adapt the device to the child growth can be a lengthy process and sometimes expensive. Having the aid of additive manufacturing these prostheses can be manufactured more quicker and with more precision. At Enabling the Future, an organization that offers low-cost 3D-printed prostheses for amputees, the goal is to create a community that collaborates in an open source with 3D printable designs for hands and arms. It was created essentially with the purpose of helping children where proper medical care doesn't exist and owning a traditional prosthetic device is financially unsustainable (10).

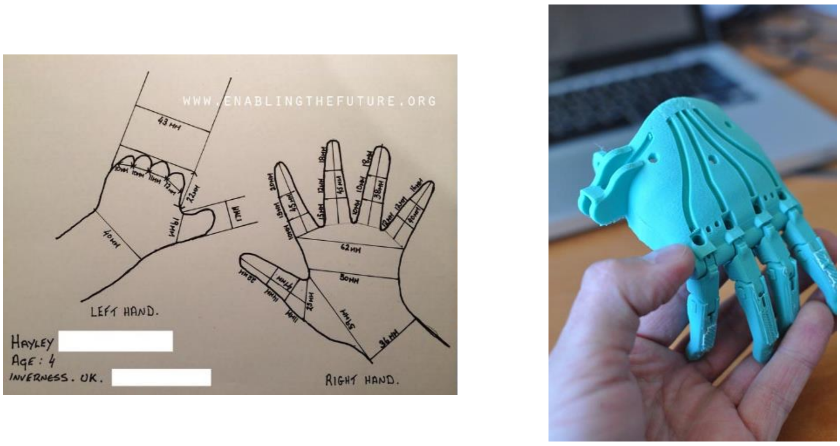


Figure 2.8 Customized prostheses made with additive manufacturing (10)

2.3 Classification of additive manufacturing processes

The Committee F42 on Additive Manufacturing Technologies in partnership with the International Organization for Standardization (ISO) classified the additive manufacturing processes into 7 different categories. The classification of the processes, that follows the norm ISO/ASTM 52900, is represented in the following Figure 2.9 (11).

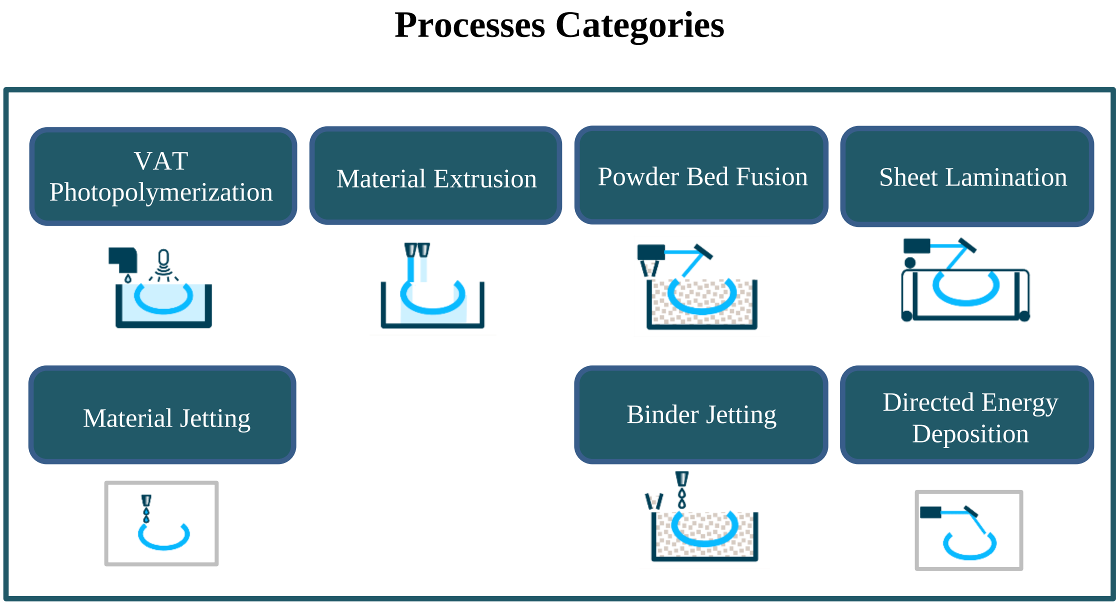


Figure 2.9 Classification of additive manufacturing processes (11)

VAT Photopolymerization

The process consists in a vat of liquid photopolymer resin that is cured layer by layer with an ultraviolet (UV) light while the platform moves the object downwards. Various other types of radiation may be used to cure commercial photopolymers such as gamma rays, X-rays, electron beams and sometimes visible light. The type of the light will depend on the material used and can be diffused via laser or projector. After the process is finished the vat is drained of resin and the object is removed. UV light may be used in post-processing for a final cure process to ensure a high-quality part. The two of the main advantages of VAT Photopolymerization technology over other additive manufacturing technologies are part accuracy and surface finish. The main limitation of the technology is the part strength (12) (13).

The alternative and commercial names of the technologies related to this process are SLA (Stereolithography Apparatus), DLP (Digital Light Processing), 3SP (Scan, Spin, and Selectively Photocure) and CLIP (Continuous Liquid Interface Production) (12).

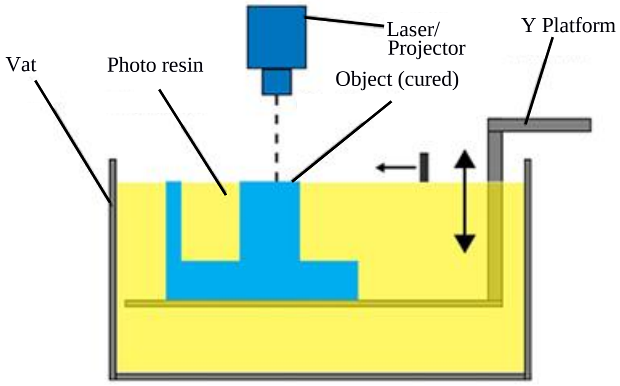


Figure 2.10 Schematic representation of VAT Photopolymerization process- adapted (14)

Material Jetting

Material Jetting creates objects using a method similar to the one that is used in an ink jet printer that we have at home. Droplets of material are deposited layer by layer onto the platform using either a continuous or Drop on Demand (DOD) approach. The material layers, that are normally made of polymers or waxes are cured using a UV light (12) (15). Material Jetting is an ideal process to create aesthetic prototypes and tooling, as it delivers full-color and multi-material parts with high dimensional accuracy. In other hand, its mechanical properties don't allow to build functional parts (16).

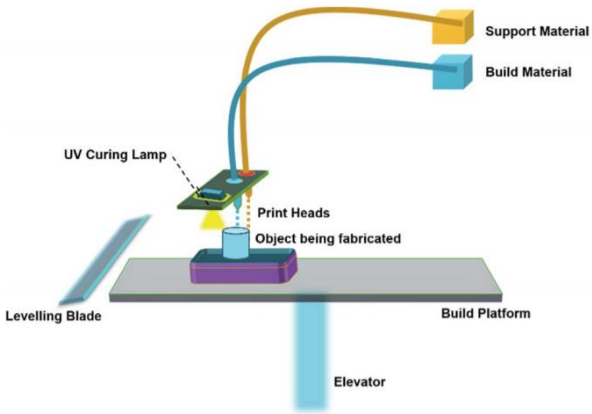


Figure 2.11 Schematic representation of the Material Jetting process (17)

Some of the commercial names of the technologies that are related to this process are Polyjet, SCP (Smooth Curvatures Printing), MJM (Multi-jet Modeling) and Projet (12).

Material Extrusion

This process is one the most widely used in additive manufacturing since is the method that is used in most low-cost desktop printers. The process uses polymer filament that goes through a heated thermoplastic extrusion and build parts layer-by-layer. The simplicity, reliability and affordability of this method have made it widely recognized and adopted by the industry, academia and consumers (18). This process is used in technologies known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) (12). For polymer additive manufacturing, the FDM process is the most frequent choice and the two polymers that are commonly used are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).

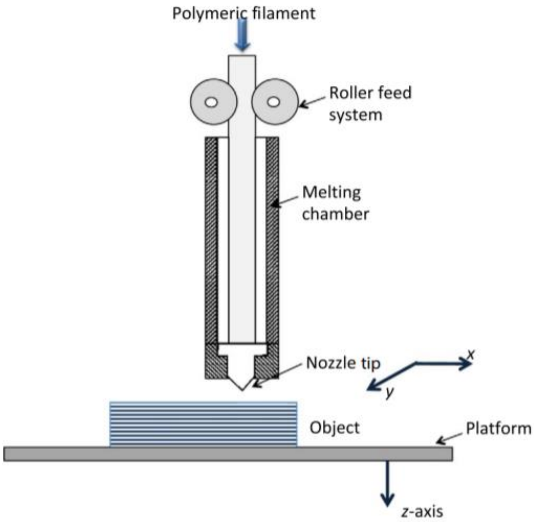


Figure 2.12 Schematic representation of the Material Extrusion process (19)

Powder Bed Fusion

Powder Bed Fusion (PBF) consists in powdered materials that are selectively melted and fused together using either a laser or electron beam. In each step a new layer of powder is spread across the previous layer using a roller or a blade. Unfused powder can be removed during the post-processing and used in a different manufacturing (20). The Powder Bed Fusion process includes the following technologies: Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Selective Heat Sintering (SHS) (12). PBF processes are widely used worldwide and have a large range of materials: polymers, metals, ceramics and composites. These processes have increasingly been used because their material properties are comparable to many engineering-grade materials used in traditional manufacturing (21).

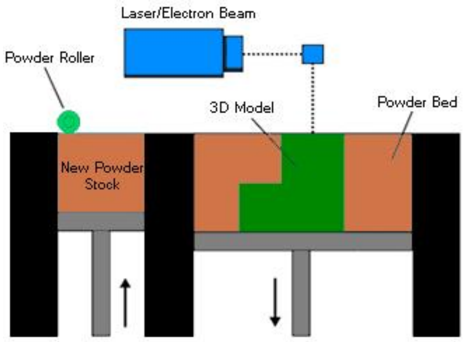


Figure 2.13 Schematic of the Powder Bed Fusion process (22)

Binder Jetting

The Binder Jetting process uses powdered material (The build material) and a binder agent. Rather than using a heat source, the binder liquid that that is selectively deposited will bond the powder layers together. After the first layer has been fused the platform moves downwards and a new layer of build material is deposited. After the part is manufactured, the material can be easily broken apart and additional post-processing works are usually necessary. To increase the strength of the part, the whole build volume (All powdered unused included) is removed and placed in a curing oven. After the process is finished the part can be removed from the powder bed. Metal or ceramic powdered parts are typically included in this second step. Other typical materials are powdered plastics, glass and sand (13) (14) (23). Some of the commercial technology names related to this process are 3DP (3D Printing), ExOne, Multi-Jet Fusion (MJF) and Voxeljet (13).

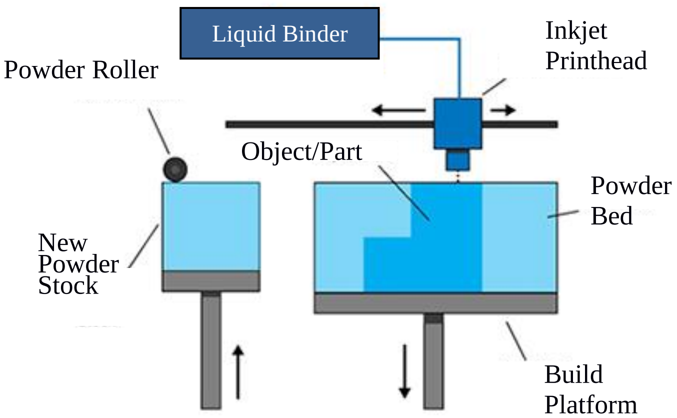


Figure 2.14 Schematic of the Binder Jetting process- adapted (24)

Sheet Lamination

In this process sheets of material are stacked and laminated together to form an object. One of the first commercialized additive manufacturing techniques was Laminated Object Manufacturing (LOM). The first LOM process involved layer-by-layer lamination of paper sheets and cut using a CO_2 laser. Some processes have been developed based on the way that the sheets are bond together and the cutting strategies. The technologies can be further categorized based on the mechanism employed to achieve bonding between layers: adhesives or chemical (In the case of paper and plastics), thermal bonding processes, clamping and ultrasonic welding (25). Normally, the unneeded material is either cut out layer by layer until the part is manufactured or the layer can be cut before to be stacked onto the next layer. In the case of metal manufacturing, the green part normally requires additional CNC machining and removal of the unbound material (13) (26).

Some of the technologies that related to this process are Selective Deposition Lamination (SDL) and Ultrasonic Additive Manufacturing (UAM) (13).

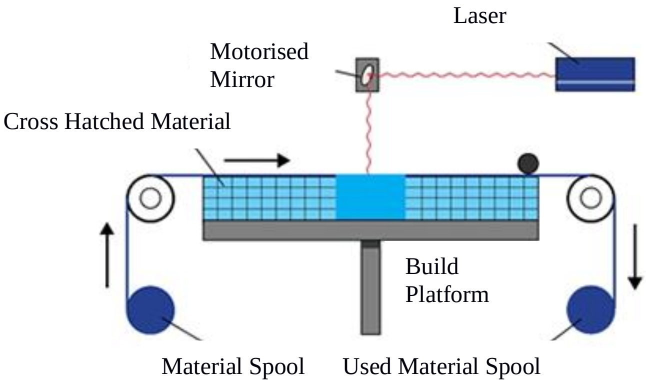


Figure 2.15 Schematic of the Sheet Lamination process- adapted (26)

Directed Energy Deposition

Directed Energy Deposition is a process that consists of a nozzle that deposits melted material with the aid of a laser or electron beam onto the specified surface, where it solidifies. The process can be used with polymers and ceramics, but it is typically used with metals in form of powder or wire. The material can be deposited from any angle due to the 4 or 5 axes of the machine (27). This method can be used to manufacture large parts but lacks in terms of resolution. Another limitation is the thermal gradient that occurs due to the high energy that affects the quality and mechanical properties of the finished part. One of the most important application of this technology is in repairing metal parts (28). Some of the technologies related to this additive manufacturing process are Laser Metal Deposition (LMD) and Laser Engineered Net Shaping (LENS) (13).

A)

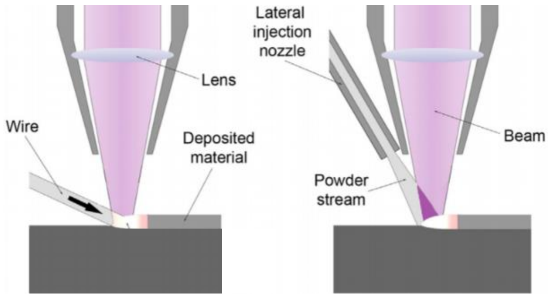


Figure 2.16 Representation of Direct Energy deposition process: the material can be deposited in form of a wire (A) or as a powder (B) – adapted (29)

Comparison of the different categories

The following table represent some of the strengths and downsides of each category process in additive manufacturing.

Table 2.2 Examples of strengths and downsides of each additive manufacturing process

Process Category	Strengths [30]	Downsides [30]	Build volume example (Machine example)
VAT Photopolymerization	-High building speed -Good part resolution	-Over curing scanned line shape -High cost for supplies and materials -Build volume	140 x 79 x 100 mm (Envisiontec Vida) [31]
Material Jetting	-Multi-material manufacturing -High surface finish	-Low-strength material	490 x 390 x 200 mm (Objet 500 Connex 3) [15]
Material Extrusion	-Inexpensive extrusion machine -Multi-material printing	-Limited part resolution -Poor surface finish	1000 x 800 x 650 mm (Insstek MX3) [31]
Powder Bed Fusion	-High accuracy and details -Fully dense parts -High specific strength & stiffness -Powder handling & recycling	-Support and anchor structure -Fully dense parts -High machine & material cost	381 x 330 x 457 mm (3S Systems ProX 500) [20]
Binder Jetting	-Full-color objects printing -Wide material selection	-Require infiltration during post-processing -High porosity on finished parts	400 x 250 x 250 mm (Exone X1 25PRO) [32]
Sheet Lamination	-High surface finish -Low material & machine costs	-Long post-processing processes	256 x 169 x 150 mm (MCor Matrix 300 plus) [26]
Directed Energy Deposition	-Repair of damaged parts -Functionally graded material printing	-Require post-processing machine	1000 x 800 x 650 mm (Insstek MX3) [27]

2.4 Bionic design

Bionic design has received more attention in the last years with the growth of additive manufacturing. The designs are inspired by nature and try to explore the configuration and the structure of the living organisms. These designs can fully exploit the maximum benefits from AM to improve the performance of the manufactured part in its application. The designer must choose the adequate structure for the goal desired. (Figure 2.17)

	Properties	Application
 Rhubarb	Bending stiffness	Beams and bars
 Bamboo	Bending and torsional stiffness	Beams, bars, axes and shafts
 Diatom	Pressure resistance	Surface structures
 Honeycomb	Pressure resistance	Sandwich structures, energy absorbers

Figure 2.17 Examples of properties and application of bionic structures - adapted (33)

In the example below the structural biomimetics was used to substitute the conventional design. The part was printed in a titanium aluminium alloy with an additive manufacturing technology and successfully passed the requirements of the structural tests. Moreover, the optimized part allowed to reduce its original weight on 26% (34). (Figure 2.18)

Figure 2.18 Bamboo structure used in optimized design (34)

2.5 Support structures

Support structures can have a high impact on the material used that will influence the build time, the post-processing time and the cost of manufacturing. Additionally, the support structures can also have an adverse effect on the surface finish of the part due to the post-processing methods that may need to remove it from the part. The process to optimize the design in order to reduce the amount of support structures is very important. This requires having in mind the position chosen for the part on the build plate and to consider the build orientation while designing. (Figure 2.19)

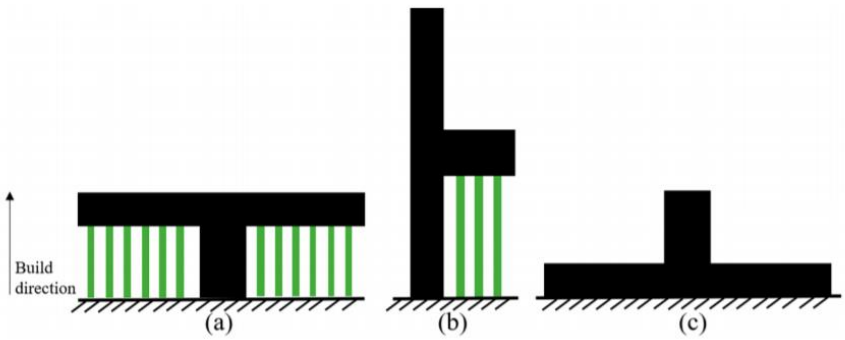


Figure 2.19 Support structures for additive manufacturing. Part in black and support structure in green color (23)

In metal additive manufacturing the overhang angle on which support is added is normally 45º but this angle can vary with the technology that is used and the geometry of the part that is manufactured. For overhanging structures with larger angles that the defined overhang angle the support structures are not constructed. (Figure 2.20)

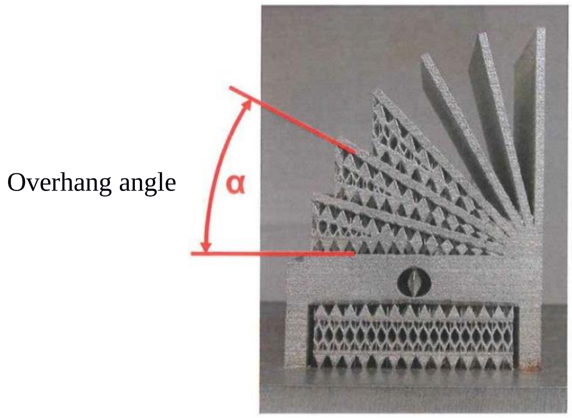


Figure 2.20 Overhang angle. Parameter selected in the printer- adapted (35)

Depending on the characteristics of the part been manufactured, the type of support structures can be changed and optimized depending on the technology and requirements. Most of the times, in order to reduce the manufacturing and finishing efforts, support structures must be optimized in terms of material consumption, strength and thermal conduction (36). Optimizing the supports structures can avoid distortions and reduce build crashes. The Figure 2.21 shows different support geometries used for SLS and SLM (37).

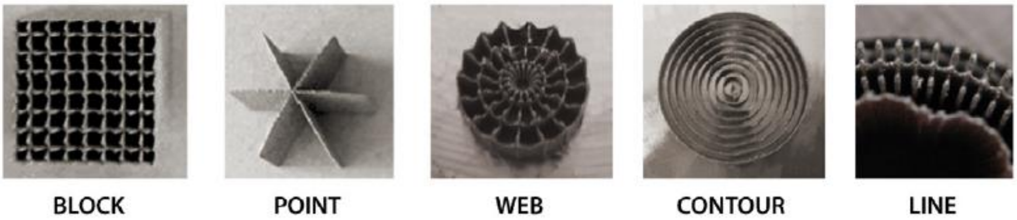


Figure 2.21 Different types of support geometries (37)

Post-processing and support removal

The methods and ease of removing the structural supports varies by the technology used to manufacture the part and the material.

The first step is to remove the part with the supports from the build plate. In the case of plastics elements, the part removal can be done with the hand or using a spatula. The methods to separate the part from the build plate for metal additive manufacturing are more complex. Generally, a wire EDM machine (Electrical Discharge Machining) or a bandsaw is used in this case.

The second step is to remove the support structures from the part. In the case of plastics, a small metal tool can do the job. There are also support structures made of water-soluble material that are easily removed by submerging the part in water. A sodium hydroxide solution or water jet can be also used. For the case of metal parts, the EDM can be also used or for simpler processes a plier, a screwdriver or a hammer will remove the supports. Innovative processes have been developed in order to transform the post-processing work into an automated process. Utilization of hydrodynamic flow or particle assisted chemical removal can facilitate the support removal and save time.

2.6 Design of lightweight structures in the aerospace industry

The principle of lightweight design can be used to reduce the weight of the aircrafts while remaining with the same functional and structural integrity. The development of innovations in airplane design can lead to tons of fuel savings. In terms of commercial aircrafts, Boeing and Airbus are in the forefront of aviation. The Boeing has sold more than 10 000 Boeing 737 while the Airbus model that is mostly used by airlines companies is the Airbus A320, having sold more than 8 000 aircrafts. These are the 2 most used commercial aircrafts worldwide (38). With thousands of these aircrafts flying in the air per day, the use of lighter materials and lightweight design can have an important impact on the materials resources needed for manufacturing and the fuel consumption on commercial air transport. Some examples are listed below, showing the use of lightweight design and additive manufacturing in commercial aircrafts.

Airbus installed in 2018 spacer panels in their A320 aircraft that are visible to passengers. The company says that the actual AM production allows a much faster small-batch manufacturing and the component is 15 percent lighter than if using conventional production methods (39). (Figure 2.22)

Figure 2.22 Spacer panels installed in A320 aircrafts (39)

Other parts used in the Airbus A320 since 2016, but this time not visible for passengers, are in a partition structure that support the jump seats used by cabin crews (Figure 2.23). The structure manufactured with additive manufacturing made in Scalmalloy, an aluminium-magnesium-scandium alloy part that weights 45 percent less than the original one. This was an important turnover for the industry and enabled the sector to show a real lightweight application of AM for commercial aircrafts (40).

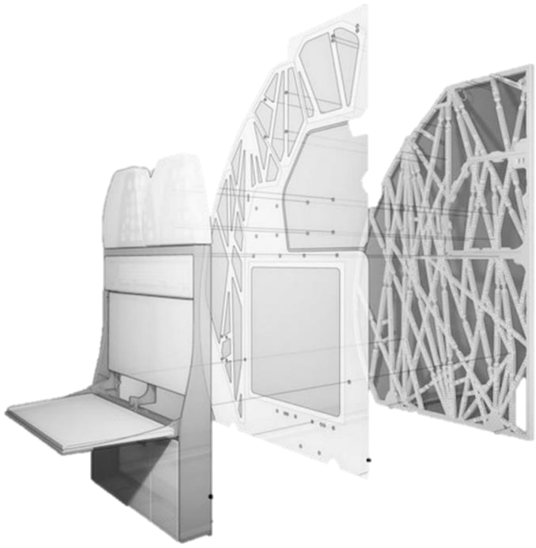


Figure 2.23 Additive partition for the Airbus A320 (40)

Boeing has already installed 50 000 3D printed that are flying on Boeing commercial airplanes but also in space and military products. The company started to research about additive manufacturing technologies in 1997. They have also invested in creating bigger parts and successfully manufactured in 2016 one tool which measures 5.3 meters long, 1.7 meters wide and 0.46 meters tall (41).

Based on the IATA (International Air Transportation Association) values, by removing one kilogram on one Boeing 737-800 aircraft is possible to save 130 EUR per year. A study estimated that by using lightweight galley carts that are 4 kg lighter that the conventional ones in a Boeing 737, the savings in fuel are worth 25 000 EUR per year on the whole fleet in all flights per year (42).

2.7 Potential and environmental impact of the technology

One important advantage of additive manufacturing (AM) comparing with the conventional subtractive method is the reduction of raw material consumption. The volume of raw material used during the additive process is very close to the volume of the manufactured part. Another benefit from this process is that the methods that use powder or liquid materials can be reused. For example, in the case of power-bed technologies, the material that was not used to manufacture the part can be recycled. The amount of waste is usually smaller than the one existing in the subtractive manufacturing process and therefore has less environmental impact (43). The air transport industry can also boost its energy savings as well as a reduction in material resources with the employment of additive manufacturing.

The aviation industry is taking measures to mitigate its emissions and as the demand for air travel continues to increase, the reduction of the aircraft's weight by using additive manufacturing technologies can have an important impact on the environment by reducing the emissions. In passenger airplanes, the use of lightweight parts manufactured with AM can provide a reduction of 4.3 to 10.3 million t equivalent of CO_2 emissions by 2050 in a mid-range adoption scenario (44).

The Figure 2.24 shows the potential energy and materials savings in the use and production phases of AM parts in passenger airplanes by 2050.

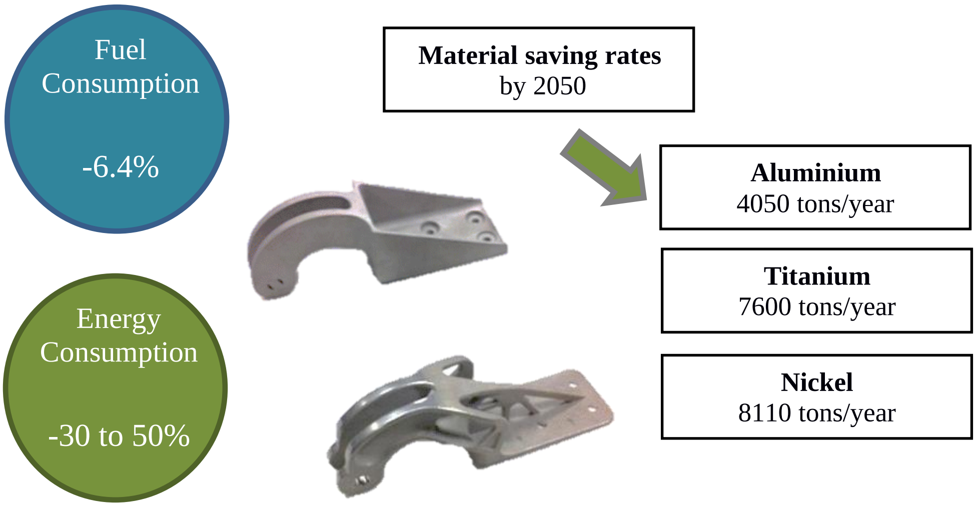


Figure 2.24 Energy saving potential of additive manufacturing in passenger airplanes (44)

2.8 Topology optimization

Topology optimization is a method that takes a 3D design space and remove any material that is not necessary for a fixed set of constraints. This design tool is used to create lightweight components and can be used during the development phase of an optimized part. This technique was boosted by additive manufacturing because the technology allows to manufacture parts with a high degree of complexity.

In the simulation workspace of Autodesk Fusion 360, a CAD/CAM software used during the internship for product design, the tool available for topology optimization is called Shape Optimization.

In the simulation study environment of the tool, the first step is to create a finite element model and select the material which will be used for the analysis.

The second step is to define the boundary conditions by selecting the structural constraints needed to apply in the model, as shown in the Figure 2.25.

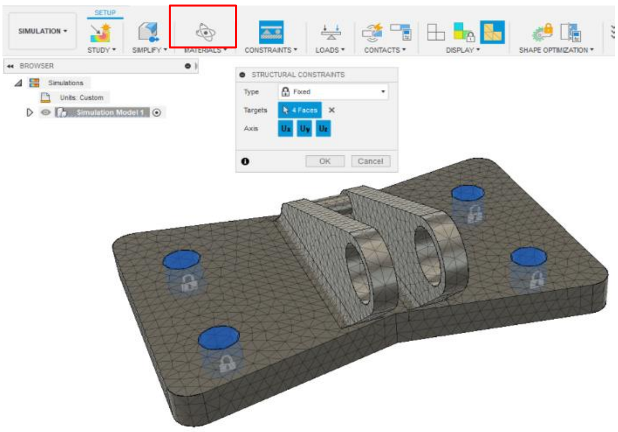
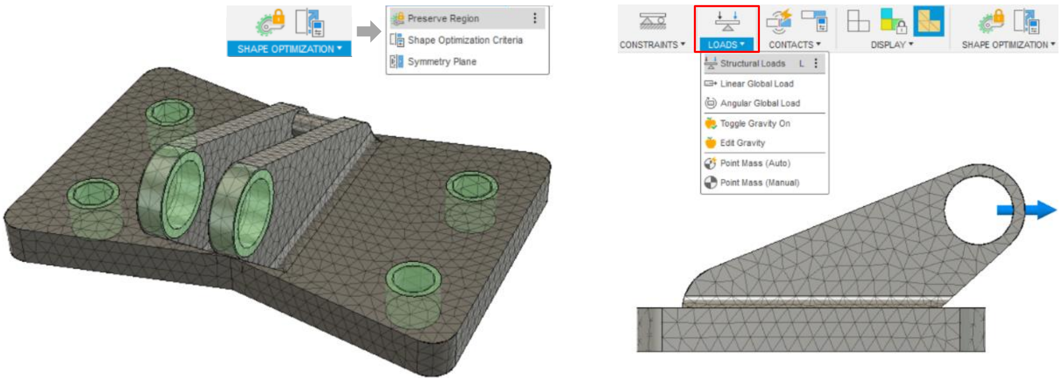


Figure 2.25 Boundary conditions in the topology optimization tool

The third step is to distinguish the regions where the optimisation algorithm can eliminate material (non-design space) and the locations where we don't want to remove any material (design space). For this steep it is used the *Preserve Region* tool- section (a) in Figure 2.26. Then the loads must also be defined using the *Structural Loads* - section (b) in the same figure.

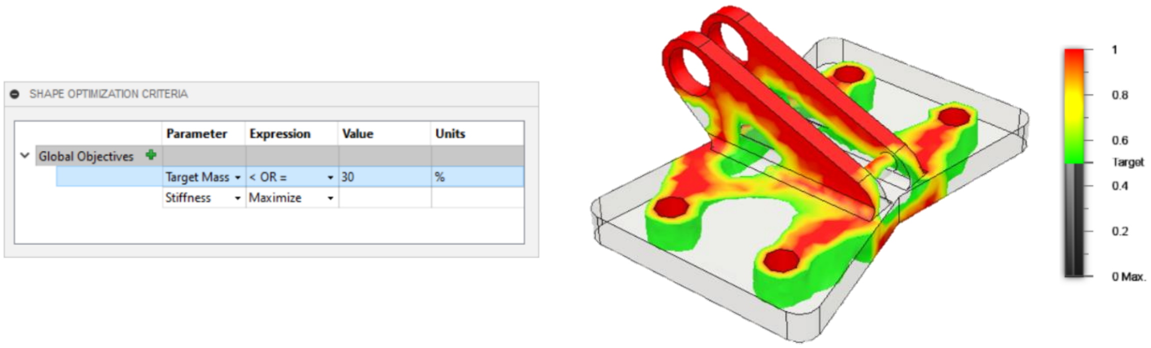


(a) Preserved regions in green

(b) Application of structural load

Figure 2.26 Preserved regions and structural loads in the topology optimization tool

In order to obtain different optimizations solutions, the target mass can be changed. It limits the mass of the optimized shape to a specified value, which is a percentage of the original mass. For this example, the target mass of 30% was chosen- section (a) of the Figure 2.27.



(a) Selection of target mass (b) Simulation result

Figure 2.27 Selection of optimization criteria and representation of optimization result

The software considered that the outputs must conform with the maximum stiffness, and this parameter was not possible to change. Nor manufacturing constraints nor maximum allowed displacement could be modified by the user.

The results of the topology optimization of Autodesk Fusion 360 are normally used as inspirations to the design of the final part -section (b) of the Figure 2.27. In the results, the absence of color represents the parts volume which are not structural relevant in that design space when red color suggests that the design space is structurally relevant.

2.9 The contribution of the dissertation

This work brings out several benefits of using topology optimization for additive manufacturing (AM) to solve real problems in the aerospace sector. The development of lightweight structures with AM can reduce significantly the amount of material and energy in comparison with traditional manufacturing processes. This reduction, especially in the development of aircraft, will have an important impact in the environment reducing its pollutant emissions during the flights. Others benefits such as reducing lead time and manufacturing difficulties and providing simpler assembly are important for the product development. Due to the rapid growth the technology, its accessibility is enlarging and a paradigm shift from design to manufacturing to design for additive manufacturing is taking place. For product development we used to wait to have the design ready before manufacturing or simulating the design. Nowadays, additive manufacturing and topology optimization bring a different possibility and allows to decide what strategy to use before getting too deep into the product lifecycle. Creations of complex and organic geometries that were never seen before in manufacturing provides new ways of looking at old problems. The methods taken by design engineers for product design will change and new approaches should be incorporated in order to avoid a lack of in-process qualification.

3. Topology Optimization of an Aircraft Bracket

This chapter includes the studies and the design of different models that were made during the main task. It includes the different topologies analyses, redesigns decisions and its structural analyses. In order to estimate the use of material and time, this chapter includes an analysis of the structural supports as well a brief distinction of resources used to manufacture the brackets. The outcome of this investigation is to find several new topologies to help to design the final bracket adapted for additive manufacturing.

3.1 Characterization of the original part

In this topic the main goal is to do a static analysis of the original part using the software Autodesk Fusion 360. The results will be used to predict if the concepts created are able withstand the loads with success and to compare the von Mises stress and displacements with the original bracket.
The CAD of the original model as well the structural loads important to be considered were given by the internship advisor.
Since the application of the bracket doesn't require large deformations and the von Mises stress are not expected do go beyond the yield strength, it was decided to run linear simulations. This kind of structural analyses are simpler and requires less computational efforts to prepare and analyze the components. As mentioned previously the bracket is situated in the airplane fuselage in a way to hold the electric cables and ceiling panels. The bracket was modeled and assembled according to the layup shown in Figure 3.1.

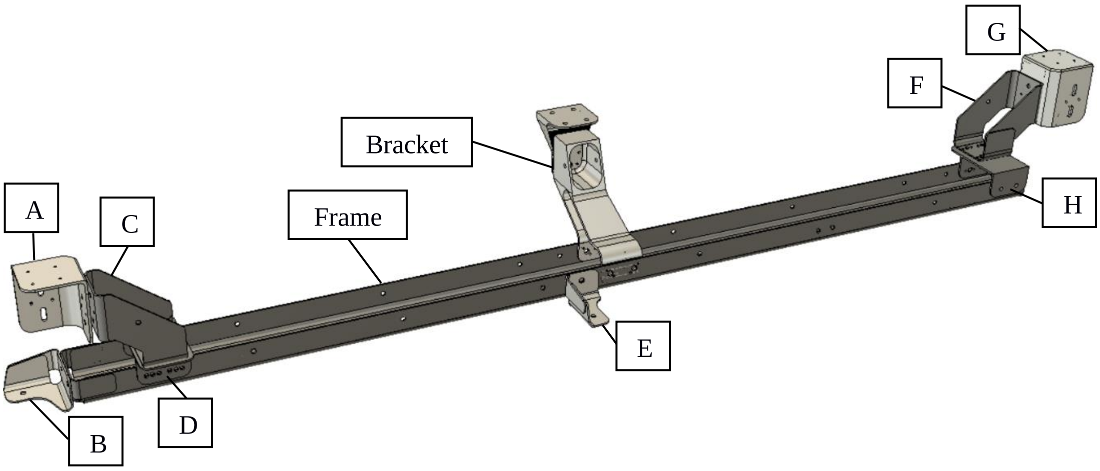


Figure 3.1 CAD model used for the development phase with 11 components

The bracket constitutes of two parts made of aluminium that is positioned in the center of the frame. The frame and the elements in dark grey presented in the Figure 3.1 are made of stainless steel while the elements A, B, E and G are made of aluminium.

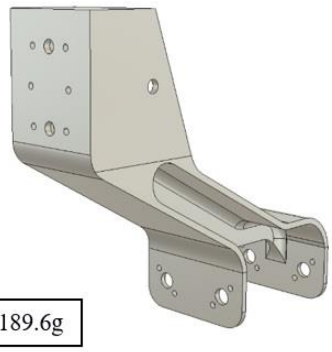
The materials used in the CAD file for the original components as well the material selected for the optimized bracket in the analyses are described in the following table (Table 3.1).
The mass is an important reference that will be used in the course of this work. For further studies and improvements of the design the goal is always to decrease the final mass of the bracket to the minimum value possible without, however, endangering the stability of the structure.

Table 3.1 Description of materials properties chosen for the development of the project

Material	**Young's Modulus (GPa)**	**Density (g/cm3)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Parts (model)**
Aluminium 6061	68.9	2.7	275	310	Bracket, A, B, G.
Stainless steel 316L	210	7.9	207	345	Frame, C, D, F, H.
Aluminium AlSi7Mg0.6	70	2.7	230	400	Optimized bracket

The masses of the bracket elements are presented in the following Table 3.2.

Table 3.2 Mass of the bracket elements

Element 1	**Element 2**
 47.4g	 189.6g
Sum = 237 g; With connecting elements: approx. **250g**	

An overview of the general dimensions of the bracket can be seen in Figure 3.2.

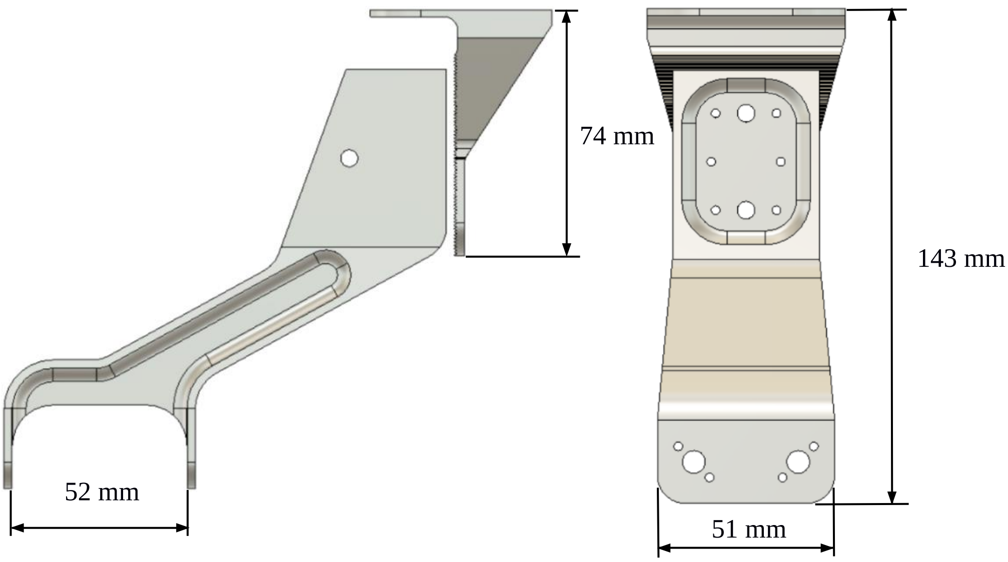


Figure 3.2 General dimensions

Connecting elements

The bracket is rigidly assembled with six aluminium head solid rivets with a diameter of 2.5 mm and two screws M5 and respective bolts and washers. The disposition of the elements of the bracket with the connecting elements can be seen in the Appendix A.1. The bracket is the assembled to the frame with another four screws M5 and its complementary elements. In order to avoid computational effort to mesh and solve solid models of fasteners parts it was used the tool “bolt connector” available in Autodesk Fusion 360 to perform the connections between the parts. These elements are represented in blue in the Figure 3.3. All the connecting elements are characterized with aluminium material.

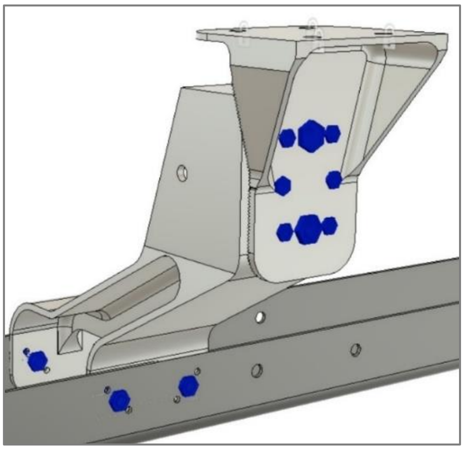


Figure 3.3 Representation of the connecting elements in Autodesk Fusion 360

3.1.1 Coordinate systems and sign convention

The global aircraft coordinate system is taken as reference for the sign convention and orientation in space. The x-axis is positive toward the back of the aircraft. The y-axis is positive toward the right of the aircraft and the z-axis is positive upward. (Figure 3.4)

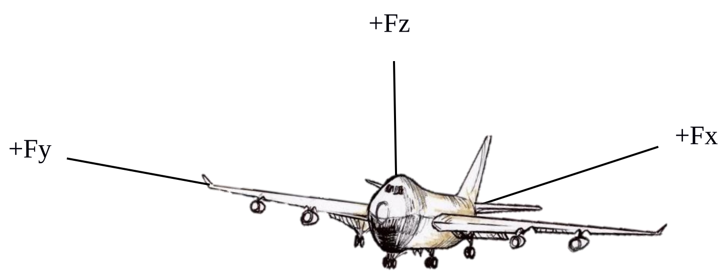


Figure 3.4 Coordinate system for static analyses

The following sign convention shown in Table 3.3 will conform the forces and relative coordinates that are used in this work.

Table 3.3 Sign convention used for the numerical simulations

Coordinate	Direction
+X	Rearward
-X	Forward
+Y	Left
-Y	Right
+Z	Up
-Z	Down

3.1.2 Structural and acceleration loads

The Figure 3.5 shows the placement of the forces for the structural analysis. In the locations 1 and 3 the loads applied are related to the weight of the cables and in 2 and 4 the loads are associated with the ceiling panel weight.

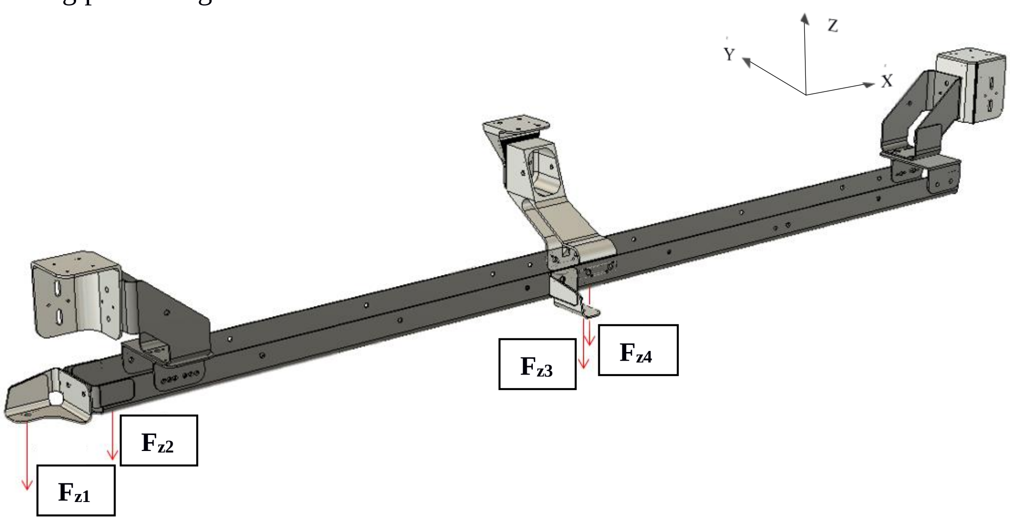


Figure 3.5 Layout of the applied loads

All the forces and load factors that needed to be considered in the application of the bracket are given in the following Table 3.4 and Table 3.5.

Table 3.4 Applied loads due to the cable's and panel's weight

Structural Load	N (newton)	Description
F_{z1}	1.47	Cables on the panel
F_{z2}	3.92	Panel's weight
F_{z3}	1.47	Cables on the panel
F_{z4}	6.82	Panel's weight

Table 3.5 Load factor limits of the Airbus A380 in G's (G-forces)

Load Case	Description	X	Y	Z
UWD	Upward	—	—	3
FWD	Forward	-9	—	—
SWD	Sideward	—	±3	—
DWD	Downward	—	—	-8
RWD	Rearward	2.01	—	—

Boundary Conditions

As boundary conditions there are three regions where it is necessary to restraint the movement in X, Y and Z. These places are the ones where the assembly will be attached to the fuselage. The application of boundary conditions can be seen in Figure 3.6.

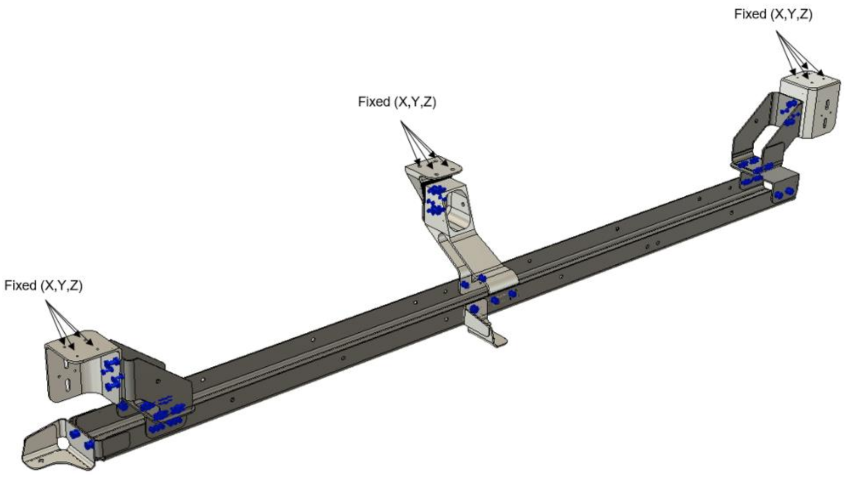


Figure 3.6 Boundary conditions for the simulations

3.1.3 Results of numerical simulations

Reference for the static analyses

The fixation between the bracket and the frame was considered as the reference in the static analysis. Due to the holes that are used to assemble the bracket to the main frame, it is expected that the von Mises stress will be higher around this region, where the bolts are present. It was assumed as the reference regions for posterior comparison with the new bracket designs. (Figure 3.7)

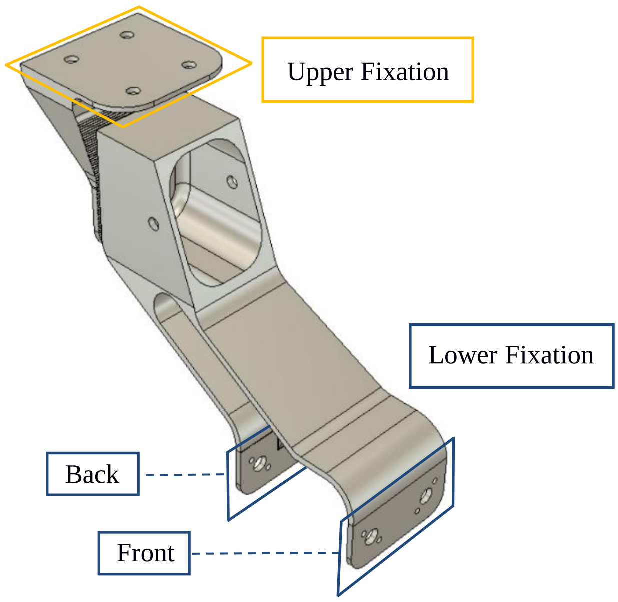


Figure 3.7 Reference regions for comparison of von Mises stress between the models

The results pretended in this section correspond to each load case. Determined the maximum values of von Mises stress, the results around the Upper Fixation are observable in the following Figure 3.8.

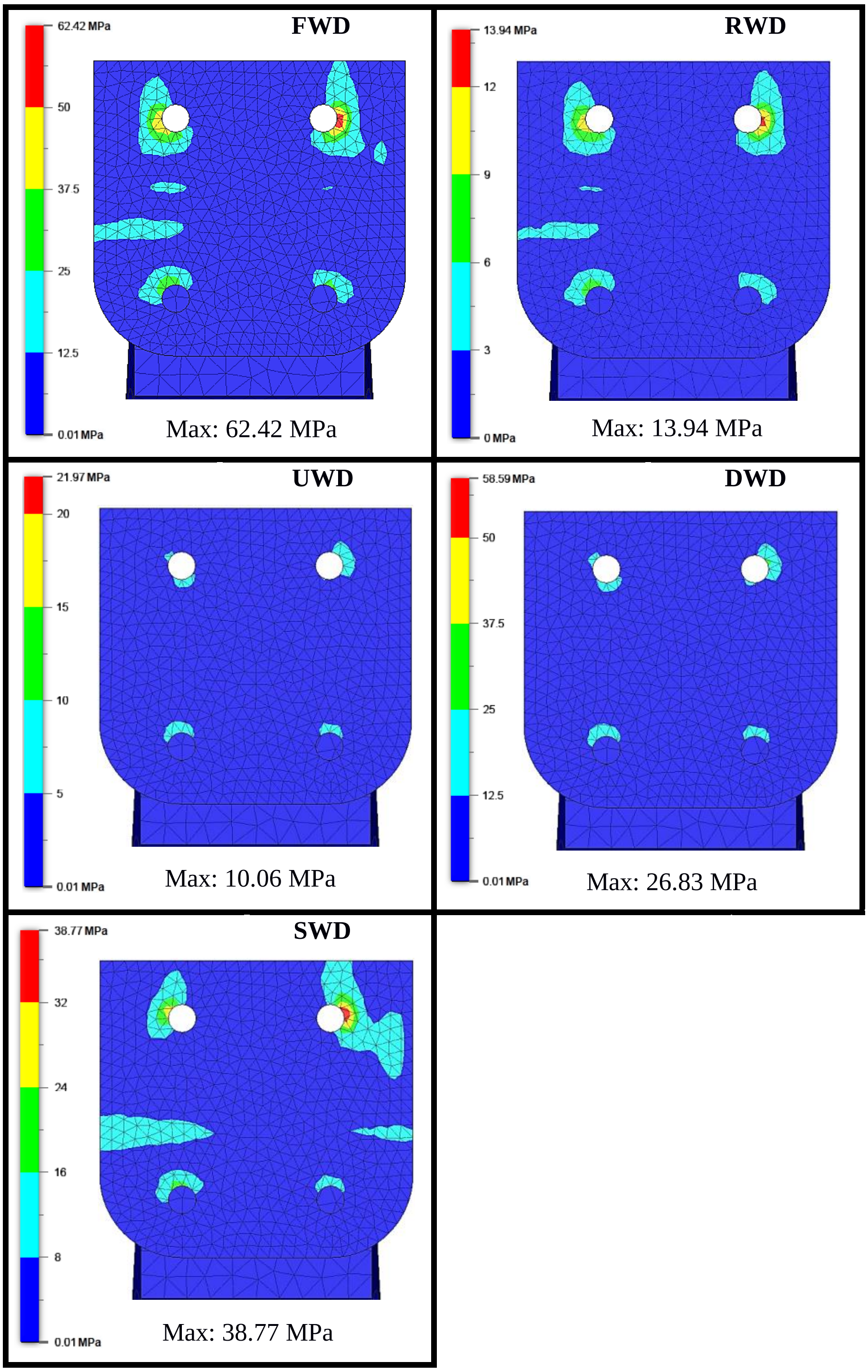


Figure 3.8 Von Mises stresses measured around the Upper Fixation of the original bracket

The results obtained for the Lower Fixation, both for the Back and Front region can be seen in the following figure.

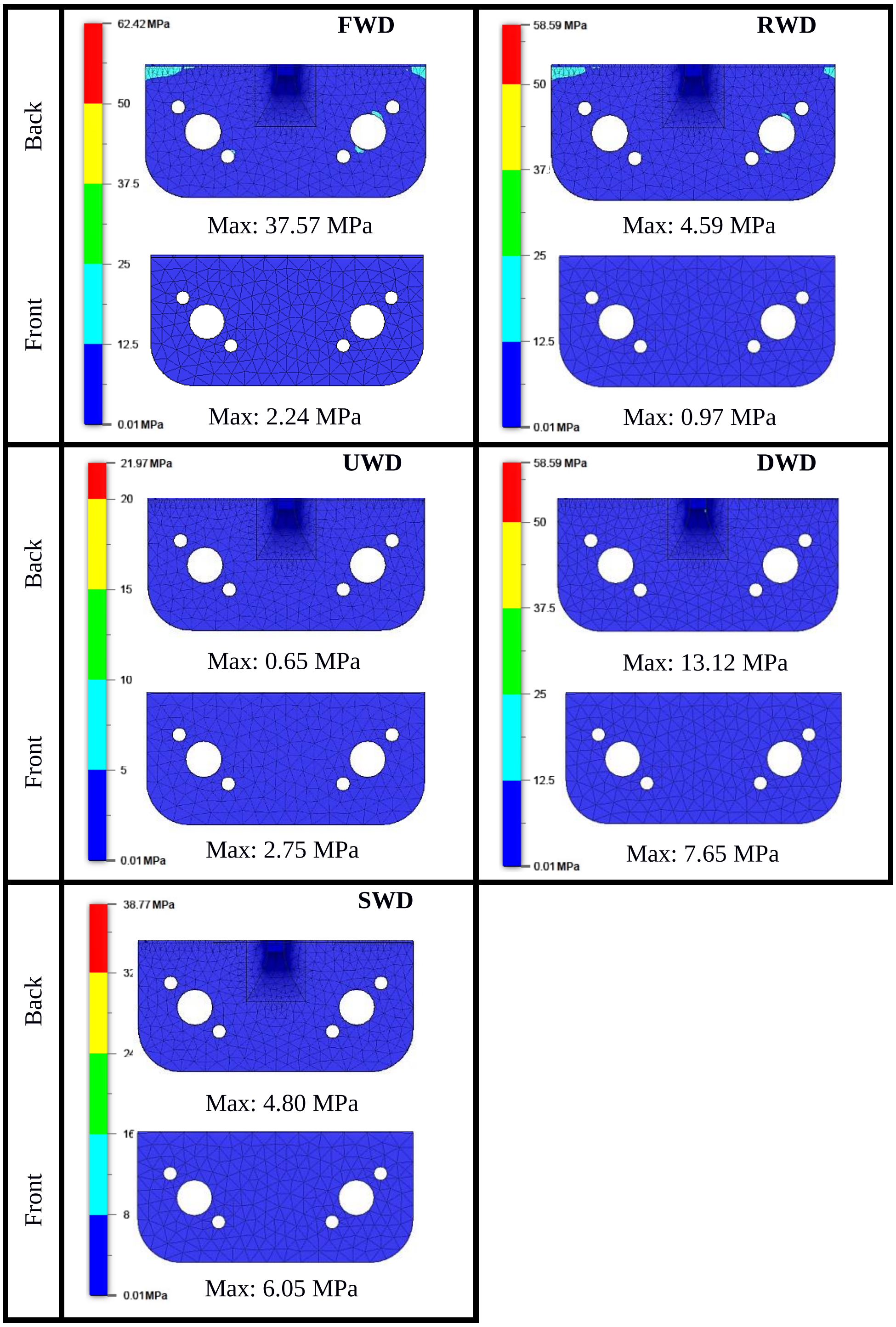


Figure 3.9 Von Mises stresses measured around the Lower Fixation of the original bracket

Regarding the obtained results for the maximum displacements, they are visible in the next Figure 3.10.

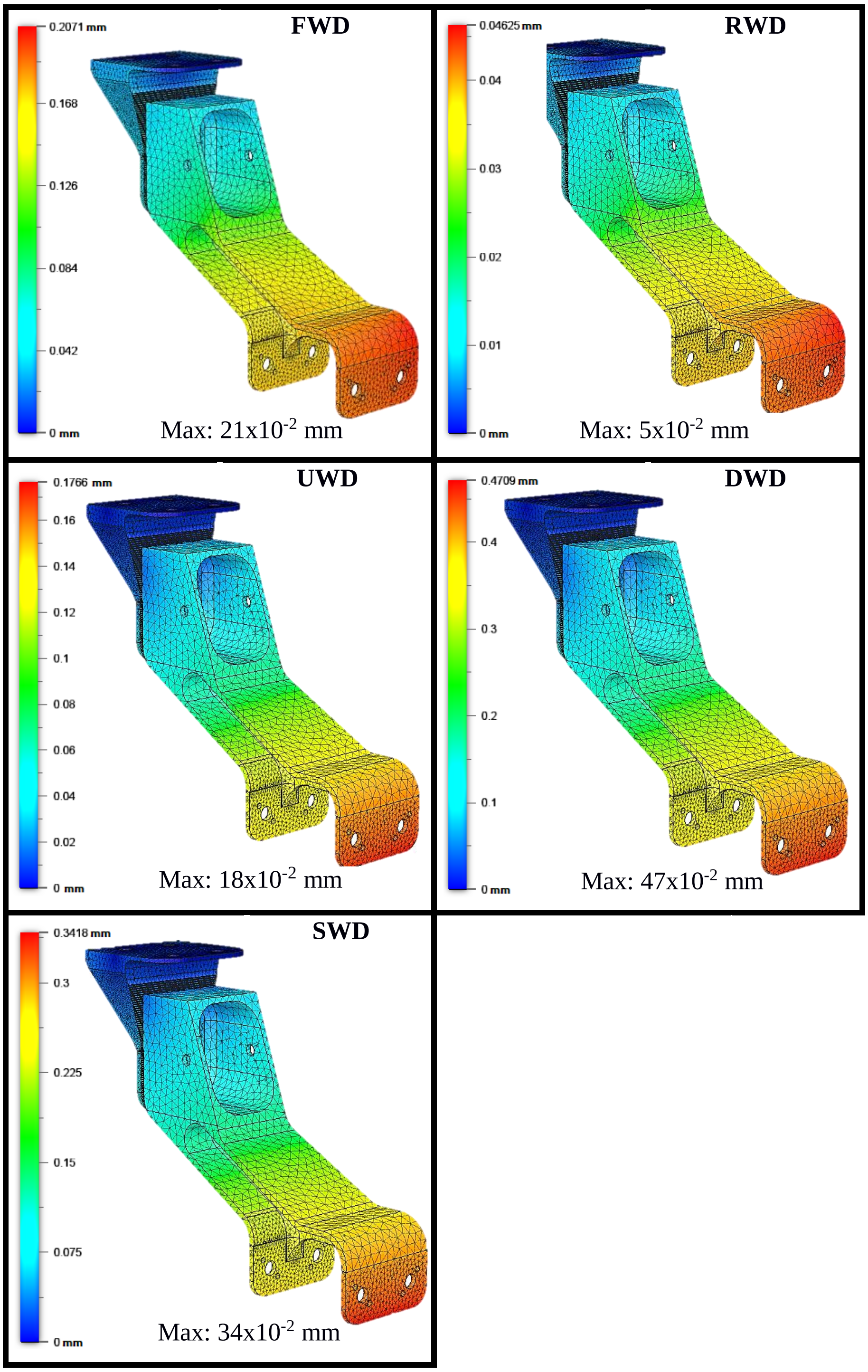


Figure 3.10 Displacements measured in the original bracket

3.2 Topology optimization analyses

The next goal was to have different outputs of the topology optimization tool that can be used as inspirations for posterior design. These are considered suggestions since some of the features that are obtained with the software tool cannot be modeled and/or manufactured with additive manufacturing technology due some of its irregular shapes and manufacturing constraints.

3.2.1 Weight minimization of the bracket

The result presented in this section correspond to the topology optimization analyses made with the software Autodesk Fusion 360. In order to have different outputs with different topologies suggestions from the software, the design space and some features of the original bracket were modified. Some versions of the original bracket were created: TO1, TO2 and TO3 are presented in the Figure 3.11 with the original model.

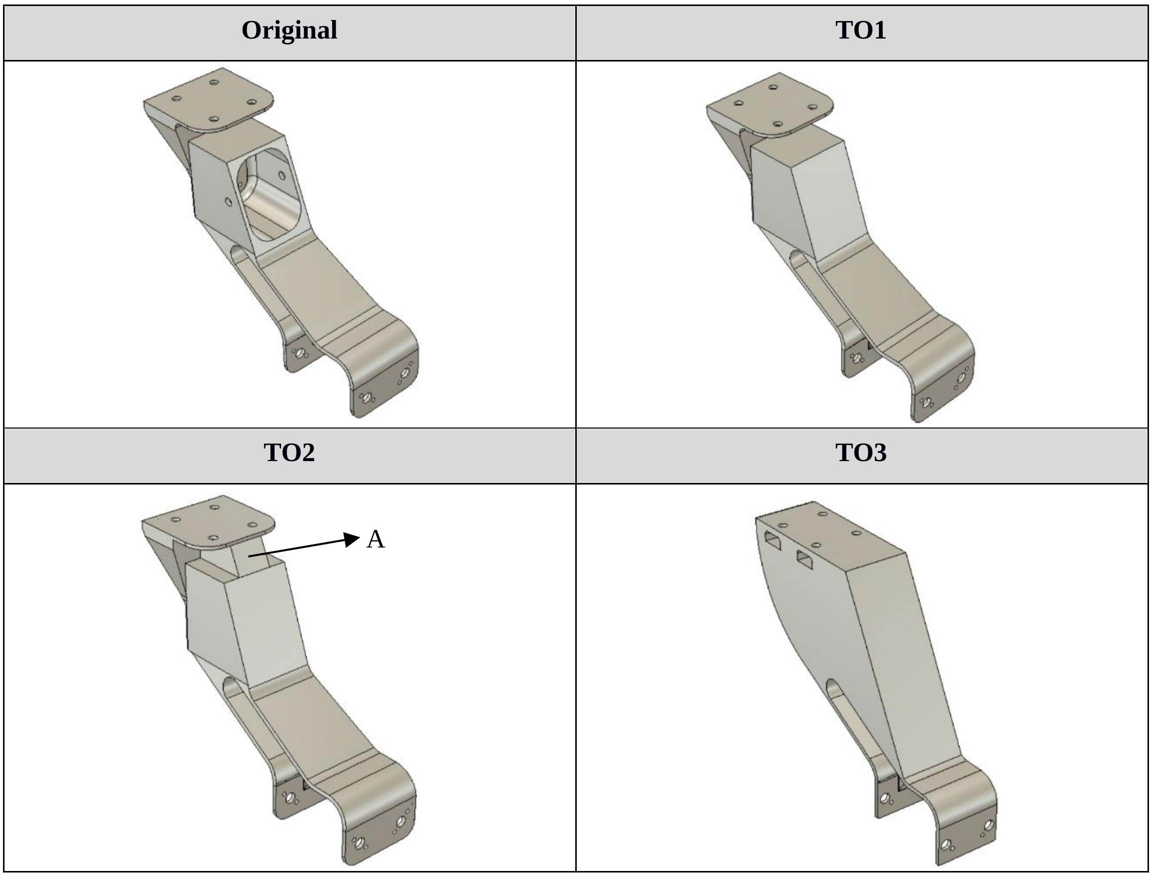


Figure 3.11 Different versions for the topology optimization studies

Compared to the original model, in TO1 the hollow cavity was filled in order to expand the number of different possibilities in that region. In TO2, the structure A (Figure 3.11) was added to increase the volume and create a different result. The major changes were made in the TO3 model where a bigger volume was created, also to reach different outputs.

For each version, the regions that needed to be preserved within the design space were the same. The 8 holes used to attach the bracket to the fuselage and to the frame were the considered regions to be preserved. The Figure 3.12 shows the preserved regions in green.

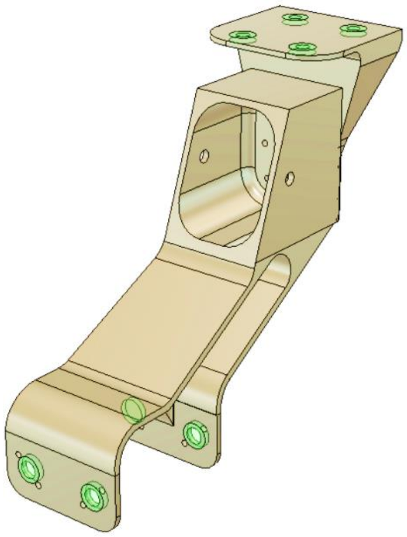


Figure 3.12 Preserved regions marked in green

The applied loads and load factors were the same as used previously. The target mass was the only parameter that was possible to change in the version of the software used for the dissertation. It represents the resulting mass of the model on which the analysis should focus to obtain. Since the mass of the versions were different and increasing from TO1 to TO3, the target mass was changed in order to have more plausible results, from 17% (TO3) to 35% (TO1).

3.2.2 Results

The figures below show the results of the topology optimization analyses.

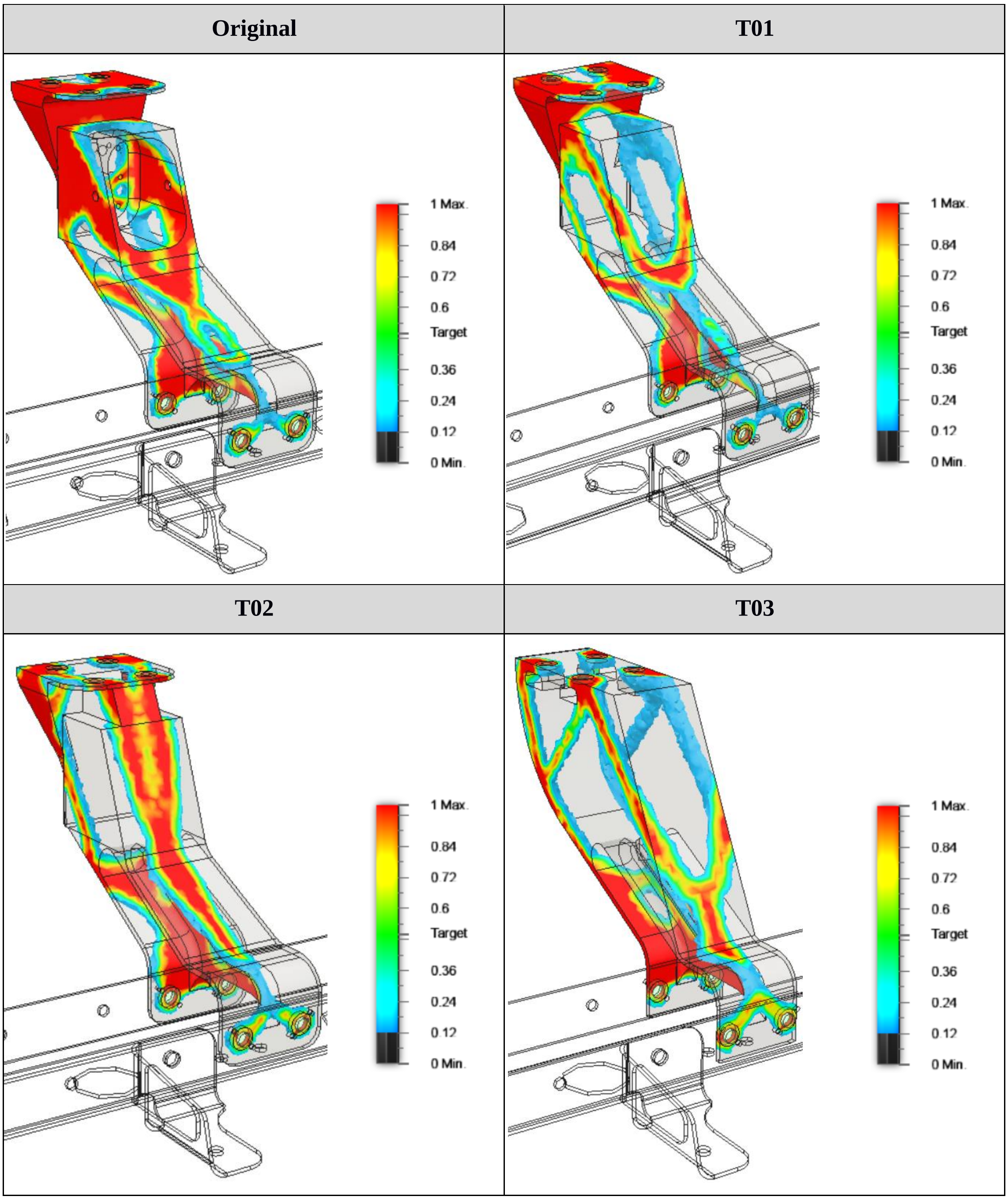


Figure 3.13 Results of the topology optimization analyses - General view

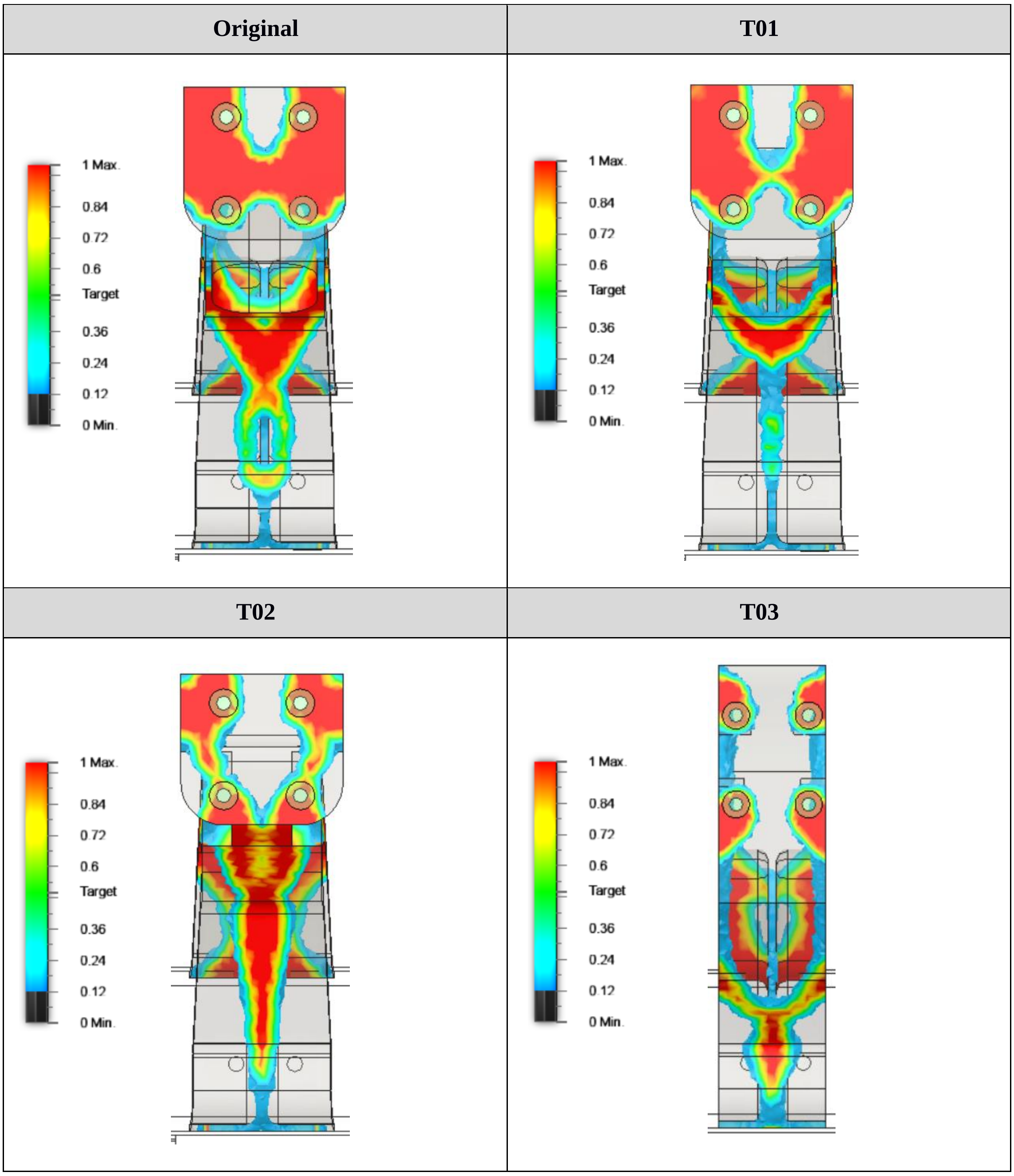


Figure 3.14 Results of the topology optimization analyses - Upper view

3.3 Development of different models

As initial stage some sketches were created to have an idea of the design that will be implement for the first optimized bracket. Through this phase it was important to analyze the requirements in terms of manufacturability.

3.3.1 Design sketching

A first approach to lightweight design was made during this stage. In these lightweight designs it was attempted to recreate shapes of tree branches and to use it for structural functions. Therefore, a geometric complex design was not simple to recreate in the CAD program and some more simpler features needed to be considered.

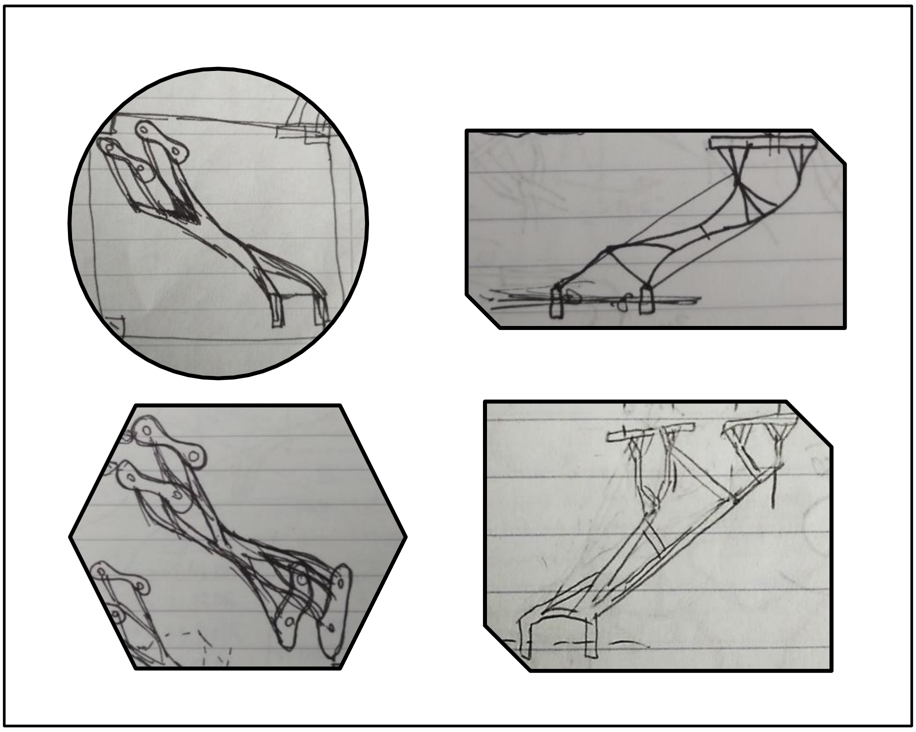


Figure 3.15 Design sketching inspired in tree branches

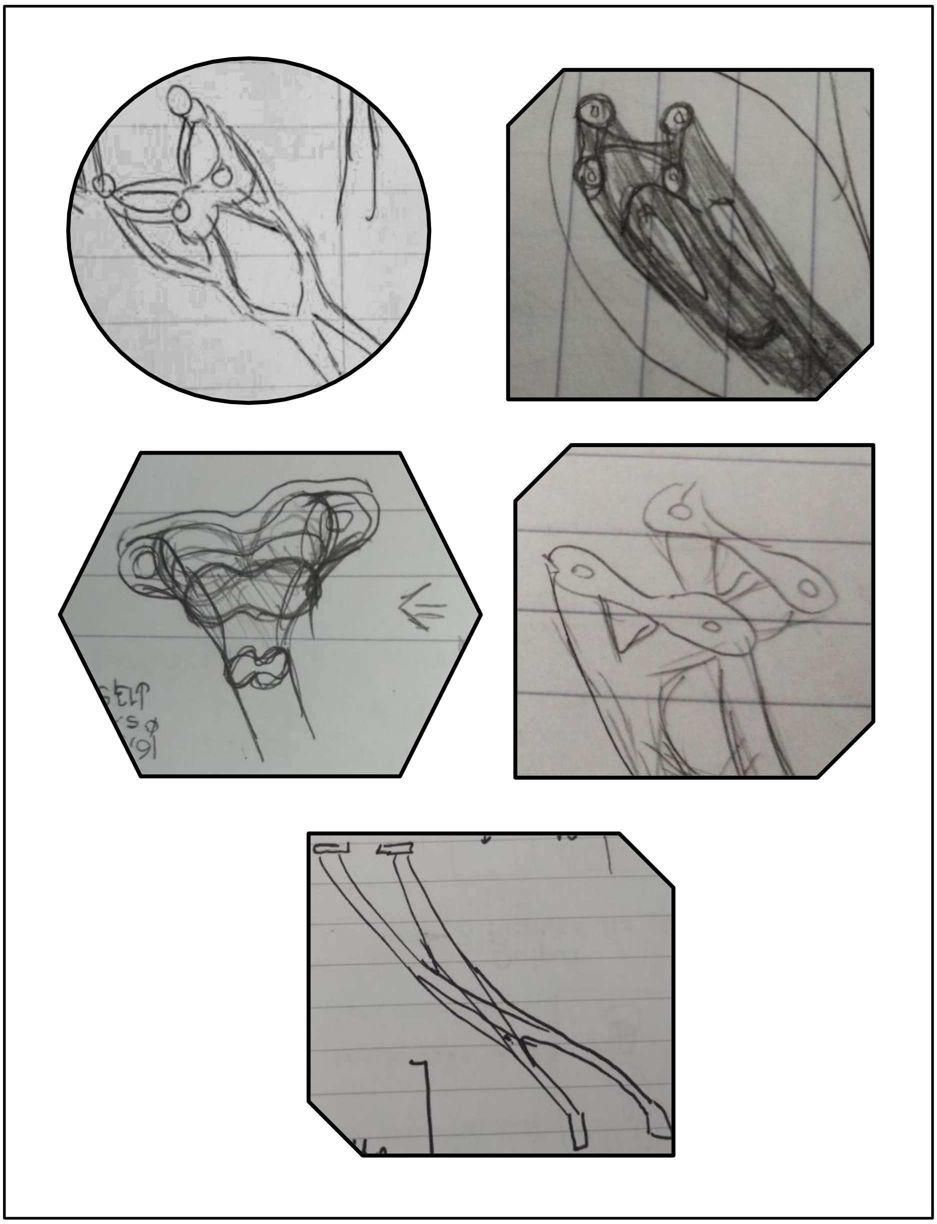


Figure 3.16 Design sketching

During the realization of the sketches it was also important to consider the orientation and that was the most challengeable part. The orientation is a major factor that will influence the amount of material support needed to manufacture the product. Another mistake made during the sketch process was to design numerous branches and thin rods shapes that can easily implement an inherent manufacturable restriction.

3.3.2 Modelling process and redesign decisions

In this part, five different bracket concepts were made. Different support analyses were made with the intention to improve the design and reduce the amount of material needed for the support structures. Others important factor that were used for the redesign of the models were their manufacturability with additive manufacturing and the volume.

The first CAD model created is presented in the Figure 3.17.

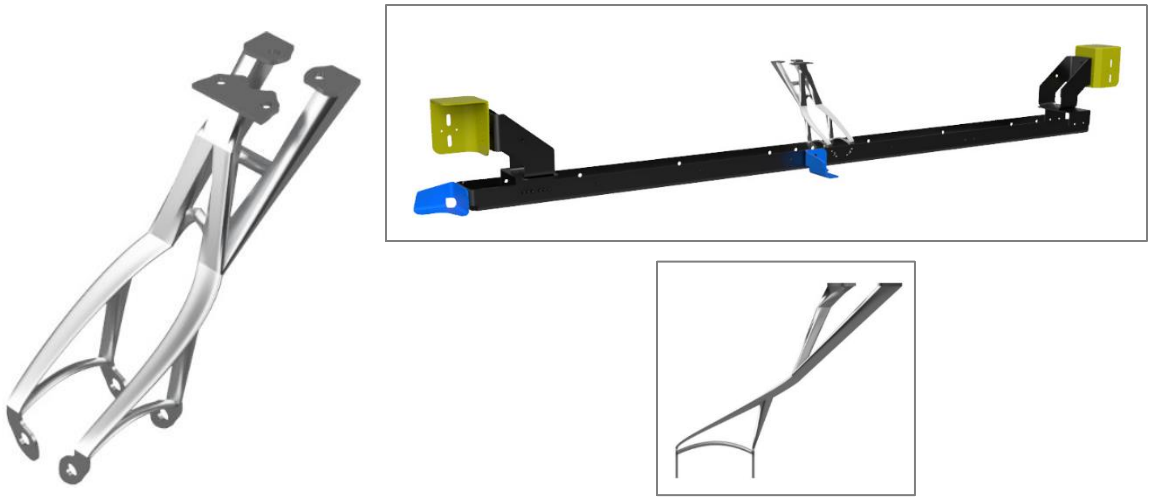


Figure 3.17 Presentation of the first model V1

Some features of this bracket were considered not appropriate for additive manufacturing, particularly the shape of the 'legs' that had sharp lines and the non-existence of smooth transitions. The smooth transitions could help for the natural growth of the part during its production and was considered important for its redesign. Some parts were also bulky, bringing the possibility to reduce its volume in posterior designs.

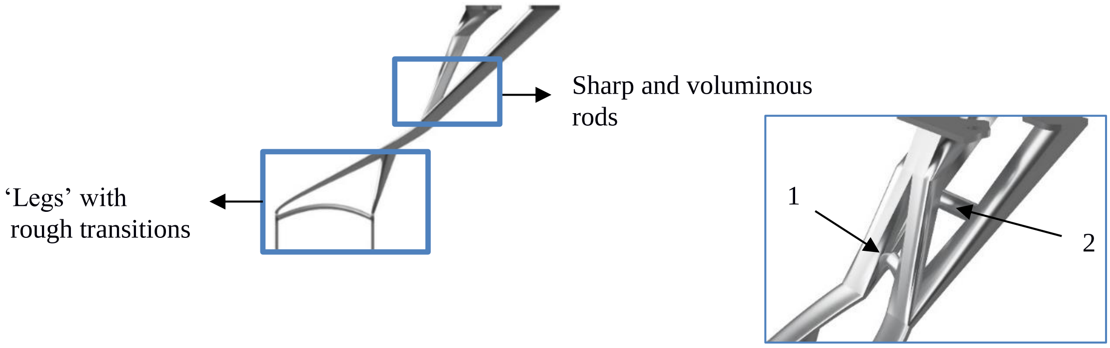


Figure 3.18 Principal characteristics of model V1 considered for the redesign

The highlighted parts 1 and 2 in the Figure 3.18 demonstrates two features that also had high volume. Additionally, these parts were not developed having considered the build orientation. Having collected the information and determined the objectives for the redesign considered the first model, a second version was created (Figure 3.19). This second model possesses considerably less volume than the first version: less 55%.

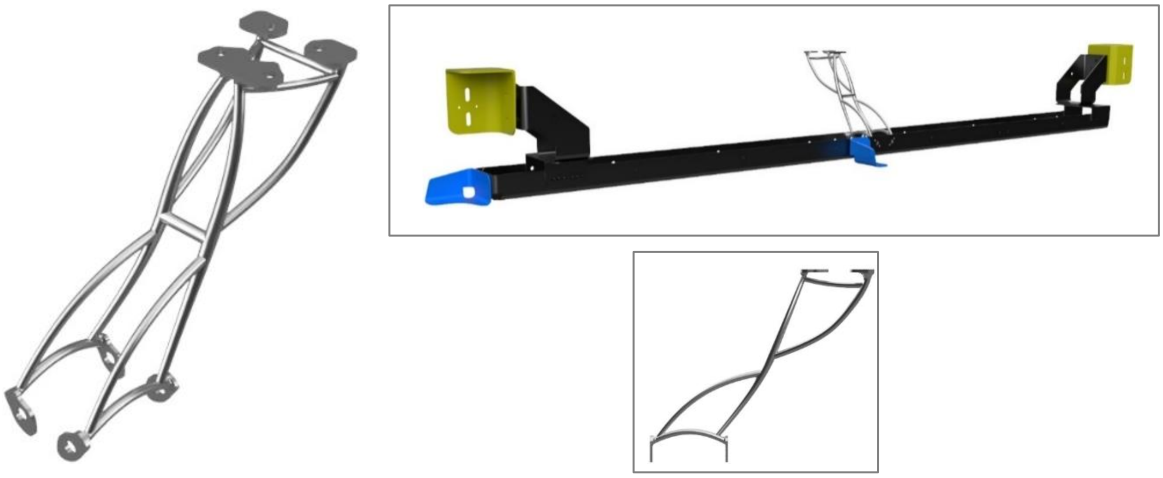


Figure 3.19 Presentation of the second concept model (V2)

During the redesign of this model, the inferior part was changed to a more curved shape. The upper part of the model was also modified in this aspect along with the reduction of its volume. Regardless these changes, some objectives for the redesign of the previous V1 were not fulfilled and new changes needed also to be worked upon.

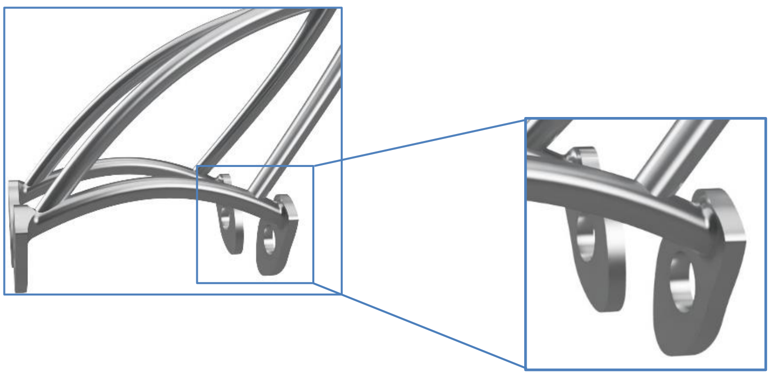


Figure 3.20 Lower fixation in concept model V2

The region of the bracket that is presented in the Figure 3.20 had rough transitions and clearly required to have a design change. In terms of the redesign objectives there are some features like the ones present in the bracket V1 that were not changed in this second version, for example the parts shown in the Figure 3.21 marked as 1 and 2.

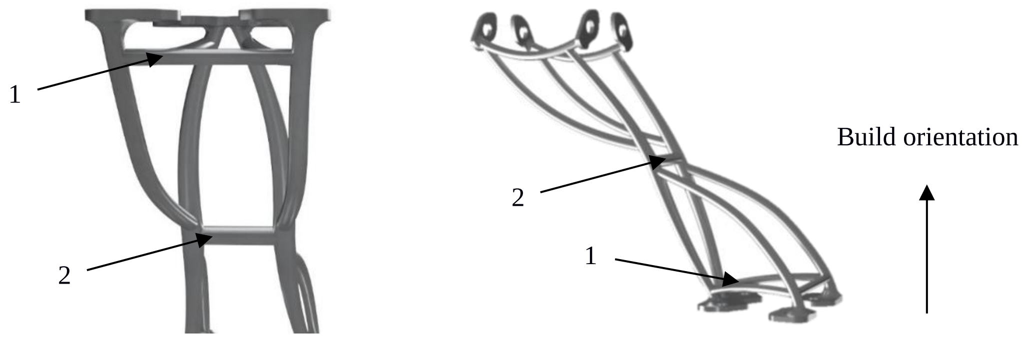


Figure 3.21 Principal characteristics of model V2 considered for the redesign

These features were not designed in a way to provide maximum potential for the natural growth of the part and were not aligned accordingly to the chosen build orientation in order to reduce the amount of support needed. This aspect was considered as one of the priorities during the redesign of the third concept.

As shown in Figure 3.22 a new bracket was created, made with special attention to the previous details that needed to be changed. This third model has a volume of 13.31 cm^3, approximately less 41% than the previous one.

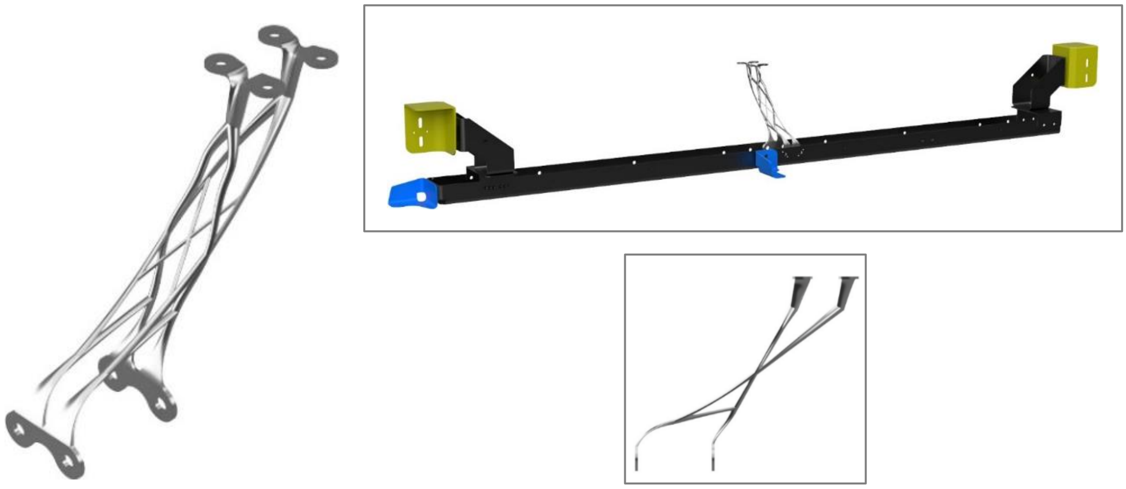


Figure 3.22 Presentation of the third concept model (V3)

An effort was made to create the maximum number of features that could be manufacture without using support structures. Smoother transitions were developed in the Lower Fixation that provides a reduction of sharp angles and amplifies the natural growth of the structure. The connection for the front holes and the back holes in the lower fixation were also developed. (Figure 3.23)

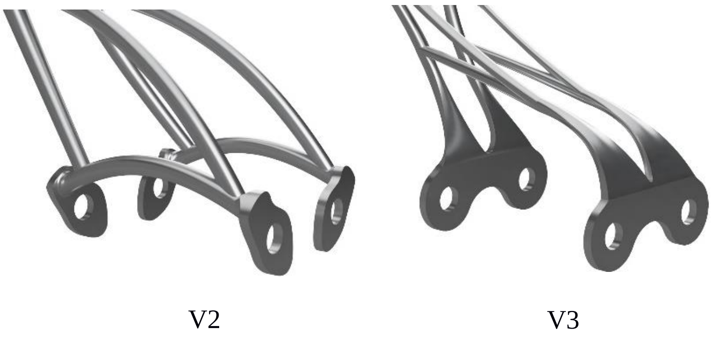
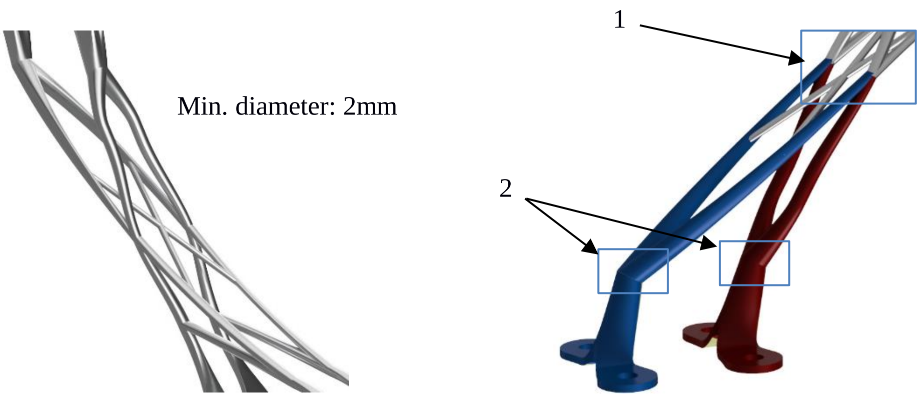


Figure 3.23 Some characteristics changed in model V3 considering the previous concept

In the Figure 3.24-a, the rods connecting the parts of the bracket were not designed horizontally but for the pretended build orientation. One aspect that had to be improved were the diameters of the rods: the minimum diameter was equal to 2 mm. Regarding to the Figure 3.24-b, it shows that the volume in blue and the one in red needed to be connected in different places since these parts were only connected through the region indicated as 1 in the Figure. Another characteristic that had to be changed are the sharp angles showed with the number 2 in the same figure. These parts, if modified to a smoother shape would have lower stresses in those regions and better results during the manufacture process as well for the post-processing works.



(a) Connecting rods (b) Potential changes

Figure 3.24 Different characteristics in model V3 that needed to be changed

As a result of the redesign needs observed from this concept and with the objective to implement a simpler design, the posterior bracket that was designed is shown in the Figure 3.25.

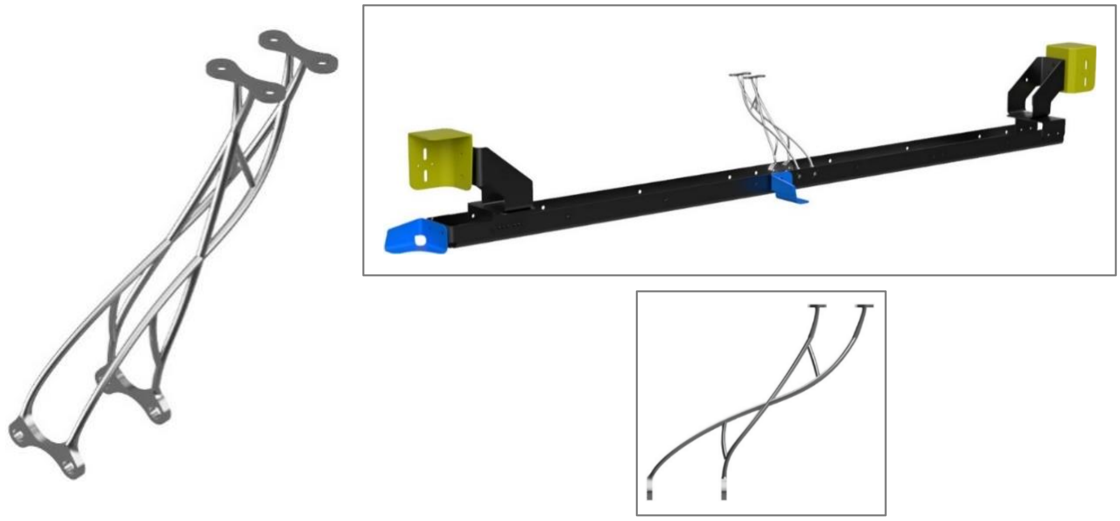


Figure 3.25 Presentation of the model V4

Some features were simplified in this version, for example the rods were designed to have a uniform form and a bigger diameter. Other connecting parts were added in order to stabilize the structure and other unnecessary ones were removed. The connecting part added were attentively located in a way to not require support (Figure 3.26). In terms of volume, this concept has roughly the same volume as the previous one: the model V3 has 13.3 cm^3 of volume while this one has 13.8 cm^3.

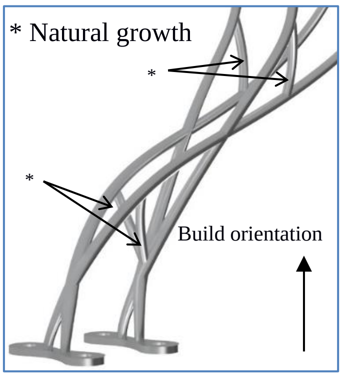


Figure 3.26 Features added to provide natural growth in model V4

It was considered that near the Lower Fixation a supplement of connecting rods was needed in order to avoid torsion of the bracket in that part. For that reason, during the redesign of the next concept some additional connections were added in that region.

As shown in Figure 3.27, a new and last version of the bracket was developed. Compared to the previous version the volume had increased 63%, from $13.8cm^3$ to $22.5cm^3$.

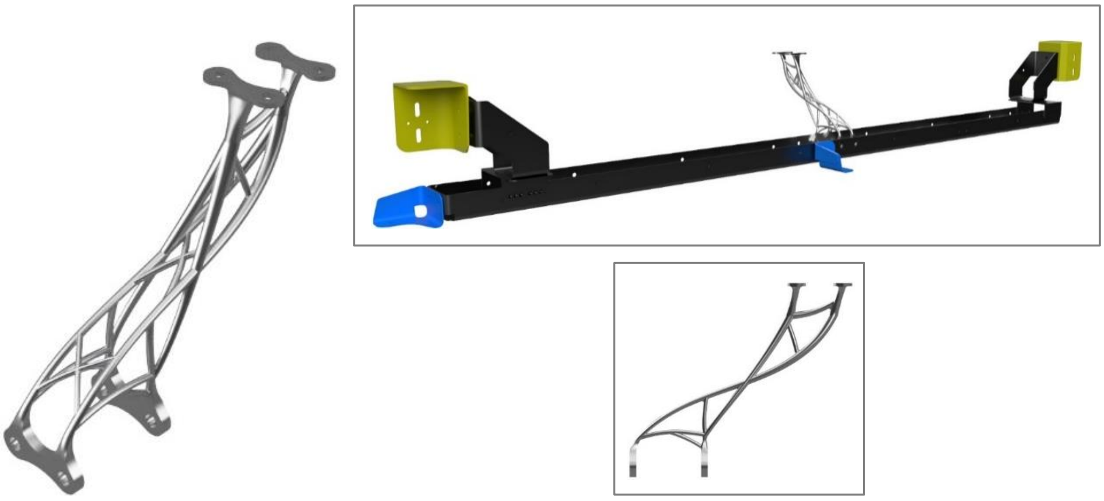


Figure 3.27 Presentation of the model V5

Comparatively to the previous design some changes were made, especially in terms of size of the Lower Fixation. The height of its front and back attachment was increased. In the previous version it had a height of 3.5 mm and was increased to 9 mm. This way the attachment with the frame is more stable since the contact surface of the bracket with the frame had increased. The design change is observable in the Figure 3.28.

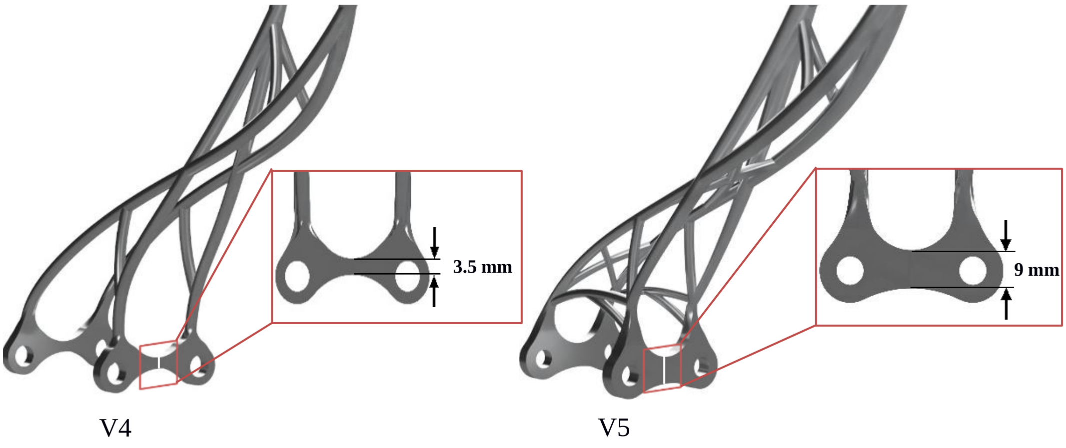


Figure 3.28 Design change in the attachment of the Lower Fixation in the model V5

Even though it was predictable that the loads wouldn't affect the structural performance of the previous model, there was the objective of developing a bracket with better structural stability without increasing largely its weight. Having manufactured a prototype of the version V4, some flexion was felt at the front part of the bracket (Region A in the Figure 3.29). For this reason, some connecting parts were added in the design. Apart from the changes that are perceivable in the figure, some auxiliary rods were added near at the symmetric plane of the bracket. These rods were configured in a "X" shape, placed in two different positions. The features can be seen in the Figure 3.30.

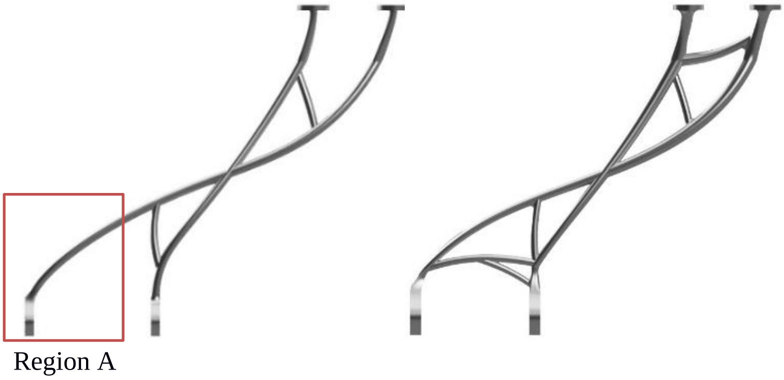


Figure 3.29 Lateral view and design changes between the model V4 and V5

This last design is chosen as the suggested bracket to replace the one manufactured with conventional methods.

Figure 3.30 Features with "X" shape in the symmetric plane in the chosen bracket design

3.3.3 Analyses of supports

This analysis, made with Ultimaker Cura, is a tentative to uncover the quantity of support needed for each concept during the manufacturing process. The amount of support needed does not have impact only on the amount of material usage but also has influence on the thermal dissipation of the part and the amount of post-processing work required.

The overhang angle is an important parameter that can be changed and determines the maximum angle which support will be added. The chosen angle depends on the characteristic of the part, which technology or equipment is applied, but the average angle used for metal additive manufacturing is 45º (26). For this reason, this angle was considered in the analyses with Ultimaker Cura. Therefore, the overhangs that have an angle between 0º and 45º the support is added. (Figure 3.31)

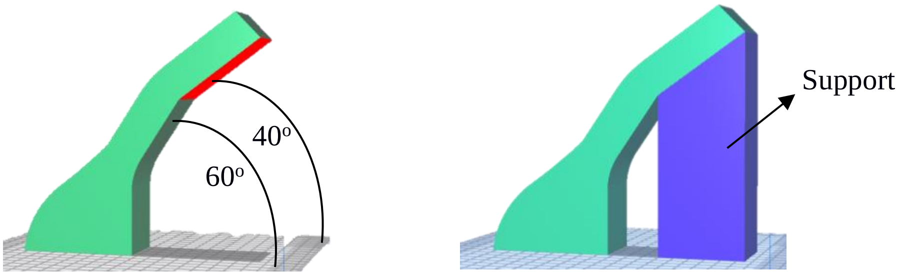


Figure 3.31 Overhang angle for support structures used for the brackets

Additionally, the build orientation used for the analyses was limited to one disposition with different build angles: 0º, 15º, 30º and 45º. It was considered to manufacture with this orientation because of the position of the holes in the Upper Fixation region (Figure 3.32). This was the build orientation taken in account during the development phase that led to many redesign decisions.

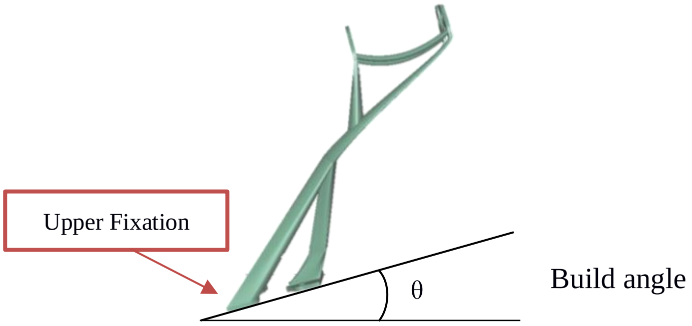
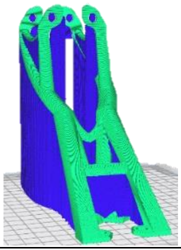
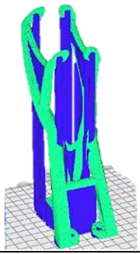
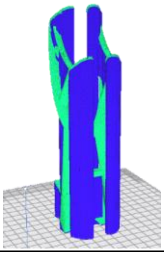
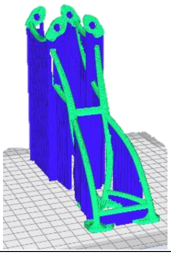
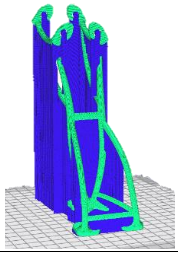
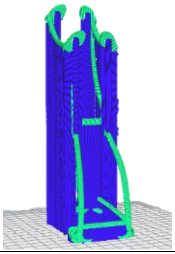
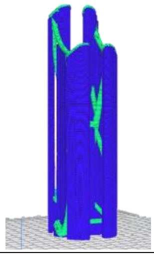
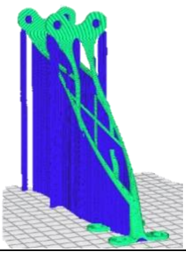
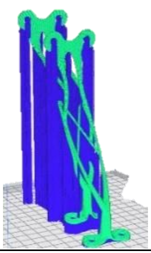
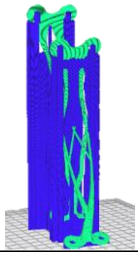
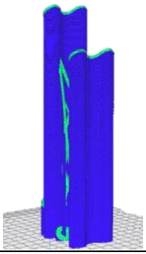
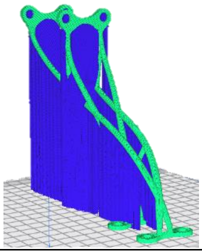
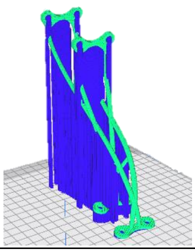
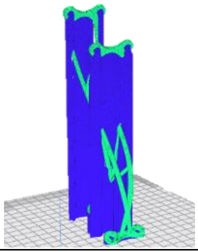
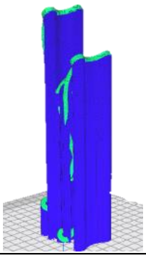
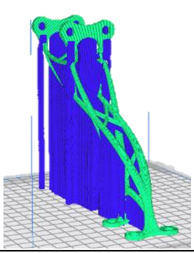
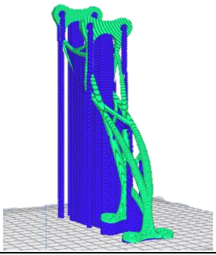
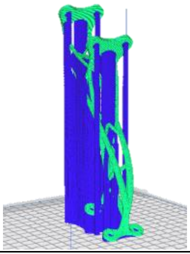
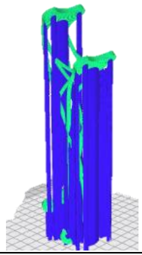


Figure 3.32 Build angle

The volume of support needed for each bracket can be seen in the following table.

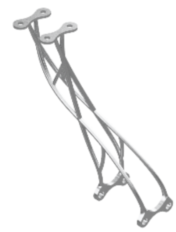
Table 3.6 Volume of support for each bracket

θ	0 º	15 º	30 º	45 º
V1				
	45.16 cm^3	38.71 cm^3	18.54 cm^3	33.06 cm^3
V2				
	28.23 cm^3	32.26 cm^3	31.45 cm^3	37.90 cm^3
V3				
	29.03 cm^3	29.84 cm^3	21.77 cm^3	34.68 cm^3
V4				
	25.03 cm^3	26.61 cm^3	22.58 cm^3	31.25 cm^3
V5				
	25.04 cm3	23.39 cm^3	20.16 cm^3	18.92 cm^3

3.3.4 Weight

This section analyzes the weight of each concept. As mentioned before, the original bracket with its connecting elements has approximately 250g and is manufactured in aluminium. Having chosen before the aluminum as the material in which the optimized bracket would be manufactured, AlSi7Mg0.6, the correspondent weights of each concepts are shown in the following table. Since a prototype of the final concept (V5) was manufactured in Polyamide (MJF), the weights of each bracket in this material is also available.

Table 3.7 Weight of each developed bracket in aluminium and polyamide- units in grams (g)

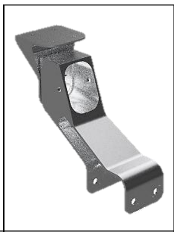
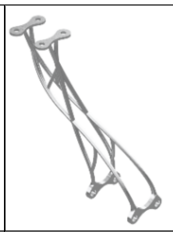
					
Material	**V1**	**V2**	**V3**	**V4**	**V5**
Aluminium AlSi7Mg0,6 2.7g/cm^3	133.1	60.5	35.9	37.3	60.8
Polyamide (MJF) 1.01g/cm^3	49.8	22.6	13.4	13.9	22.7

3.4 Results of structural analyses

3.4.1 Von Mises stresses

According to the references regions created to compare the von Mises stress between the original model and the concepts created, the results are presented in the following table. The image results with more details of the analyses can be found from the Appendices B.6 to B.10.

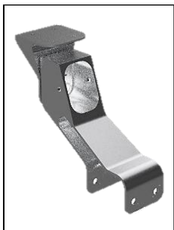
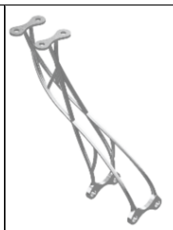
Table 3.8 Maximum von Mises stress for each bracket in MPa

						
Load Case	**Original**	**V1**	**V2**	**V3**	**V4**	**V5**
FWD	62.42	15.94	23.37	10.79	34.22	24.32
RWD	13.94	3.37	4.43	2.41	14.68	8.27
UWD	10.06	5.37	8.37	5.92	16.11	5.26
DWD	26.83	14.07	14.46	15.52	43.29	14.03
SWD	38.77	17.86	12.68	20.13	24.91	14.86

3.4.2 Displacements

The calculated displacements of the developed bracket with the comparison with the original model are observable in the following table. The image results of the displacement analyses are shown from the Appendices B.1 to B.5.

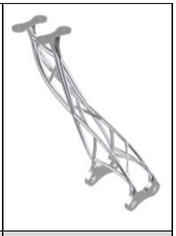
Table 3.9 Maximum displacement for each bracket (x10^{-2} mm)

						
Load Case	**Original**	**V1**	**V2**	**V3**	**V4**	**V5**
FWD	21	6	21	24	32	16
RWD	5	1	5	5	7	7
UWD	18	3	11	13	9	14
DWD	47	7	30	37	24	35
SWD	34	8	21	45	31	37

3.4.3 Buckling analyses

The critical buckling loads obtained are presented in the following table.

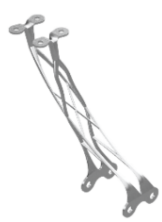
Table 3.10 Critical buckling loads

						
Load Case	**Original**	**V1**	**V2**	**V3**	**V4**	**V5**
FWD	42.3	65.6	21	7.4	7.7	24
RWD	174.5	227.5	123.8	32.2	33.8	171.8
UWD	293	155.6	54	63.9	73.5	334.2
DWD	62.9	31.5	17.2	18.6	21.2	48.5
SWD	87.7	131.7	62.8	44.7	57.2	78.6

3.4.4 Safety factor

In this results section is displayed the safety factors calculated in each bracket.

Table 3.11 Safety factors

						
Load Case	**Original**	**V1**	**V2**	**V3**	**V4**	**V5**
FWD	8.49	15	15	15	10.7	13.6
RWD	15	15	15	15	15	15
UWD	15	15	15	15	15	15
DWD	5	15	15	6.6	9.3	8.5
SWD	8	15	9.4	5.9	10.5	8.3

3.5 Analyses of resources and methods

A time analysis and material resources analysis are resumed in the section below. The quantity of material and time for metal additive manufacturing are not possible to predict with the slicer software Ultimaker Cura. The results indicated below are calculated for the manufacturing of the brackets in PLA, a plastic used in the FDM printers. An infill density of 100% was used for each bracket. These results are an indication of the effects of the usage of the support and compares the material and time resources between the models.

3.5.1 Material and time

Table 3.12 PLA material consumption calculated for the FDM printer Ultimaker 3

Developed Brackets	Build Angle	Support (g)	Part (g)	Total (g)
V1 	**0º**	36	62	98
	15º	31		93
	30º	15		77
	45º	27		89
V2 	**0º**	23	28	51
	15º	26		54
	30º	25		53
	45º	31		59
V3 	**0º**	23	17	40
	15º	24		41
	30º	18		35
	45º	28		45
V4 	**0º**	21	18	39
	15º	22		40
	30º	18		36
	45º	25		43
V5 	**0º**	20	28	48
	15º	19		47
	30º	16		44
	45º	15		43

Table 3.13 Time consumption calculated for the FDM printer Ultimaker 3

					
Build Angle	**V1**	**V2**	**V3**	**V4**	**V5**
0º	14h 24min	8h 24min	6h 51min	6h 17min	9h 34min
15º	13h 42min	9h 11min	7h 17min	6h 25min	9h 25min
30º	12h 24min	9h 08min	6h 01min	5h 26min	9h 03min
45º	13h 08min	9h 17min	7h 25min	6h 43min	8h 34min

3.5.2 Prearrangement for manufacturing

As a further influence on the costs, the alignment in the build chamber of the machine plays an important role regarding the cost-effective manufacturing of the part. Depending on the disposition of the brackets, the number of parts that can be manufactured simultaneously will vary. By position the brackets in the orientation that was before mentioned and with a build angle of 0º or 15º, it is possible to place up to 16 brackets in the build chamber. If the build angle selected is for example 30º or 45º, it is possible to place 28 brackets on the build plate- Figure 3.33 and Figure 3.34. This significantly reduces manufacturing costs and time per unit.

For this prediction an EOS M 400 metal additive manufacturing machine was used. It has a build chamber size of 400x400x400 mm.

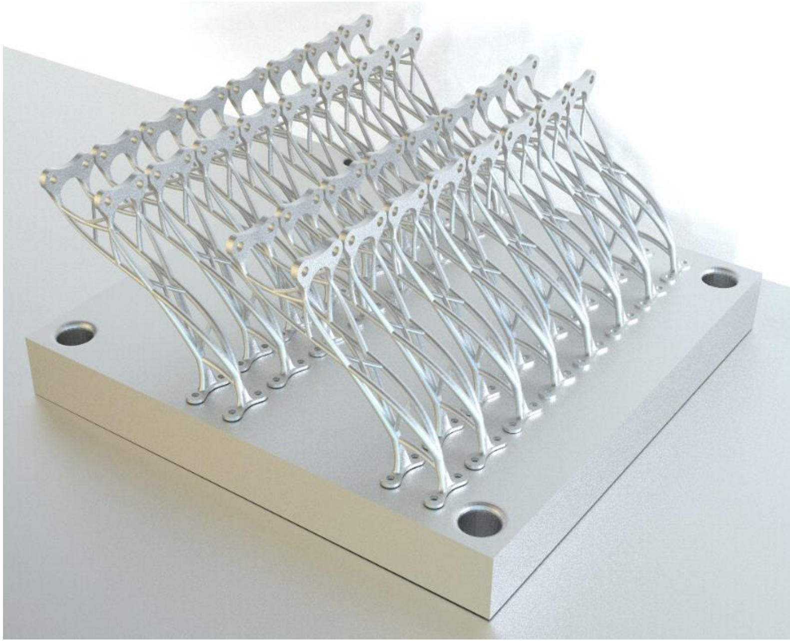


Figure 3.33 Prearrangement with defined orientation and build angle of 0º (16 units)

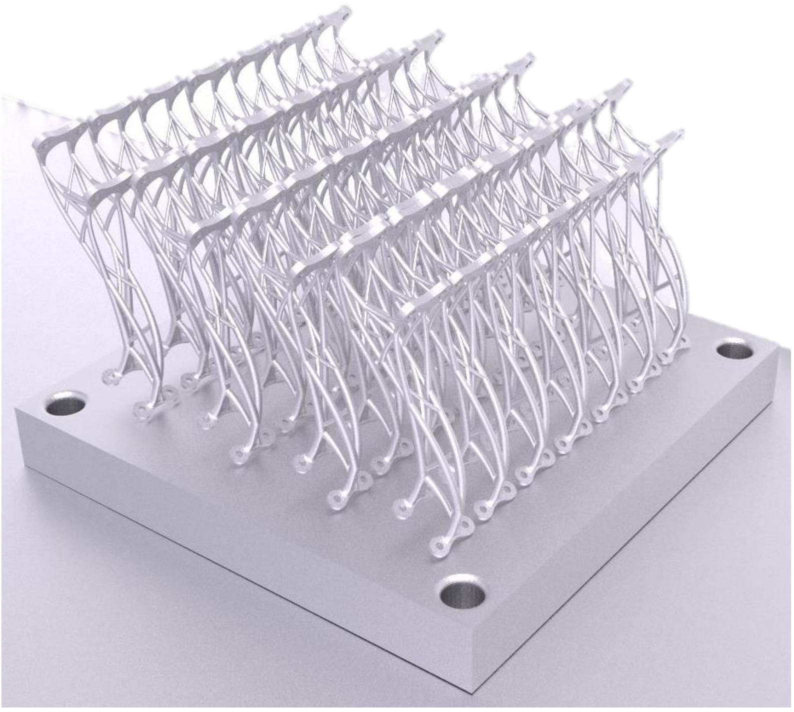


Figure 3.34 Prearrangement with defined orientation and build angle of 30º (28 units)

4. Discussion of Results

4.1 Comparison of results

The developed brackets, from the model V1 to the model V5, shows that the approach chosen to improve the design in each case was done by trial and error. At the beginning some mistakes were made, especially with the construction of voluminous parts and rough shapes in the model. These mistakes can be observable in the model V1, having the biggest weight (133.1g with AlSi7Mg0.6). The reduction of the weight on 55% from the model V1 to the model V2 demonstrates the clear intention to reduce its weight. Apart from reducing the bracket's weight, the first effort in designing for additive manufacturing is perceivable in the transition from the model V2 to the model V3. By analyzing these two brackets, it can be observed that this objective was achieved since these changes led to a reduction of 25% in the volume of supports needed.

Regarding the structural analyses, the maximum value of von Mises stress is equal to 43.29 MPa, observable in the model V4 with the downward load case. This value is below the yield tension of the aluminum selected for additive manufacturing which is 230 MPa. The results of the displacement in all brackets are also acceptable and don't cause any risk due to its low order of magnitude ($x10^{-2}$ mm).

Concerning the values of the buckling loads, the lowest factors are present in the forward load case for the model V3 and V4 (7.4 and 7.7 respectively). This does not prejudice the structural stability of the brackets but are indicating that the absence of the rods or their small diameter near the symmetric plane reduces its resistance to flexion in this load case.

In the case of the model V4, it was mentioned that having the prototype in hands some flexion was felt in the Lower Fixation region. Having added some extra rods, the results shows that the objective to increase the flexion strength was achieved since the buckling load factor had increased on average by 3 times in the model V5. This reinforcing also proved to reduce the von Mises stresses on average by 50%.

Analyzing the results of the safety factors, the results are positive since the minimum value is 5.9 in the case of the model V3. Even so, if we compare the results of the original bracket for the forward and downward load case with the ones of the model V5 (13.6 and 8.5 respectively), they are indicating that more material could be removed from the bracket.

In terms of time and material resources, the chosen design V5 present better results with the orientation of 45º. With this prearrangement the cost per unit in terms of time and material is smaller.

4.2 Validation of chosen design

The chosen design, as mentioned before, is the last bracket that was developed – the model V5. The developed bracket has 60.8g and is approximately 76% lighter compared to the original one.

The structural analyses show that the optimized part can outstand the loads and it is resistant to be applied instead of the original one. Comparing the results of the von Mises stresses, the maximum value calculated in the new bracket is 24.32 MPa in the Lower Fixation region (Forward load case). This value is does not exceed the yield tension of the aluminum chosen for the additive manufacturing printer. On average, the von Mises stresses were reduced on 52% comparing with the original bracket. The results of the displacements were not affected, resulting in a low order of magnitude as in the original bracket. Additionally, the buckling loads have been slightly reduced by 12% but the minimal load factor is 24 in the forward load case, which is acceptable and will not cause any risk of bending.

The geometry of the bracket is also acceptable and doesn't make a significant difference in the application. The optimized bracket is easier to install than the original one. Additionally, the bracket doesn't require any type of assembly. Regarding the impact in the fuel consumption, the replacement of the 200 original brackets with the optimized parts would save approximately 38 kg for each airplane. The results indicate that the bracket adapted for additive manufacturing fulfill the needs of the application and would outstand the loads and accelerations without structural problems.

5. Conclusion and Future Works

Considering the different elements developed during the internship in the main challenge and with the parallel tasks, this work proved to have required a multidisciplinary approach. In all of them required some initial research, the development of prototypes and structural tests in order to understand if the developed solution are functional and would fulfill the needs for what the product is applied for. I didn’t have any experience with the operation, manufacturing and project in additive manufacturing. In terms of skills acquired, the internship was very rich in terms of learnings and the fact that it was possible to work in a professional environment with different ongoing projects had proved to be a good experience.

This work demonstrated that the additive manufacturing technologies can reduce the lead time significantly. In very short time the CAD files can be translated to real objects to get significant feedback from the future users of the product or to test them to improve their design.

The main task of the internship proved to be a good example on how the parts manufactured with conventional methods such as CNC machining, can be optimized to be suitable for additive manufacturing. During the first weeks of this project, some difficulties were felt because to design for this technology was not as simple as predicted. Many mistakes were made, for example the build orientation was not taken in account in the first designs and that increased the volume of supports needed. A clear adaptation to the technology was necessary, and this proves the paradigm change that will occur in the future since designing for manufacturing is largely different from designing for additive manufacturing. Besides this, better decisions were made afterwards improving the design the bracket. Posterior static analyses proved that the bracket is suitable to be installed in the aircraft.

Many different adaptations, tests, and experiments have been left due to the lack of time or proper software. Future work implies a deeper analysis on the results that are possible to obtain with the different available technologies, new proposals for the design of the bracket and the study of the influence of post-processing methods. This work had been mainly focused on the use of a different design to perform an application using a different manufacturing process, leaving the study of these analyses outside of the scope of the work. The following ideas could be tested:

1. It could be interesting to adapt lattice structures in some parts of the model that could help to reduce the weight of the bracket while retaining the same structural properties. (Figure 4.1)

Figure 5.1 Example of the application of lattice structures (Blue color) (45)

The design of these features is complex and time-consuming, and this leads to the necessity to use an adequate software. Reducing volume of the bracket in some parts may lead to significant savings.

2. It would be useful to manufacture the prototype of the bracket in metal in order to study some characteristics of the part that could lead to some design changes. The main reason is that by the observing the surface roughness (After the support removal) or any warping effect (Due to residual stresses during the cooling process) could be reduced or avoided by changing the design of some features. Residual stresses can endanger the safety of the process and can result in a cancelled process. Static analyses of fatigue strength for the different build orientations are also required in order to study the need of a heat treatment to improve the mechanical properties of the part.

3. The support structures can be optimized in order to obtain different benefits. Using an appropriate software, the geometries of the supports can be changed, creating lattice geometries or scaling the supports differently that would allow to reduce material usage and enable an easier support removal. Since the support removal is an important time-consuming labor, the optimization can reduce the post-processing time and improve the surface quality of the bracket. In addition, some different examples of the supports could be analyzed in order to secure a

consistent solution that would allow an effective usage of material and time without compromising the quality of manufacturing.

4. The development of a parametric modeling could be created in order to adapt the bracket to an equivalent function where local changes exists or even in a different application. The ability to change the dimensions and shape of the model based on the needs of the specific application can greatly save time and development costs. For example, if the application of the developed bracket is required in a different airplane, the dimensions of the fuselage will change and rapidly the height of the bracket could be modified. The demand of parametric solutions that is suitable for additive manufacturing enables the transition towards an automated fabrication.

These 6 months were a good introduction to the industry and to the potentials of this technology. Besides the autonomy given by the internship's supervisor, he was always available to answer any kind of question. The company had also exceeded the expectations. The adaptation to a new country and different language were challenging but the acquirements are worth the effort involved. It is an experience that would recommend to anyone who is considering choosing this path.

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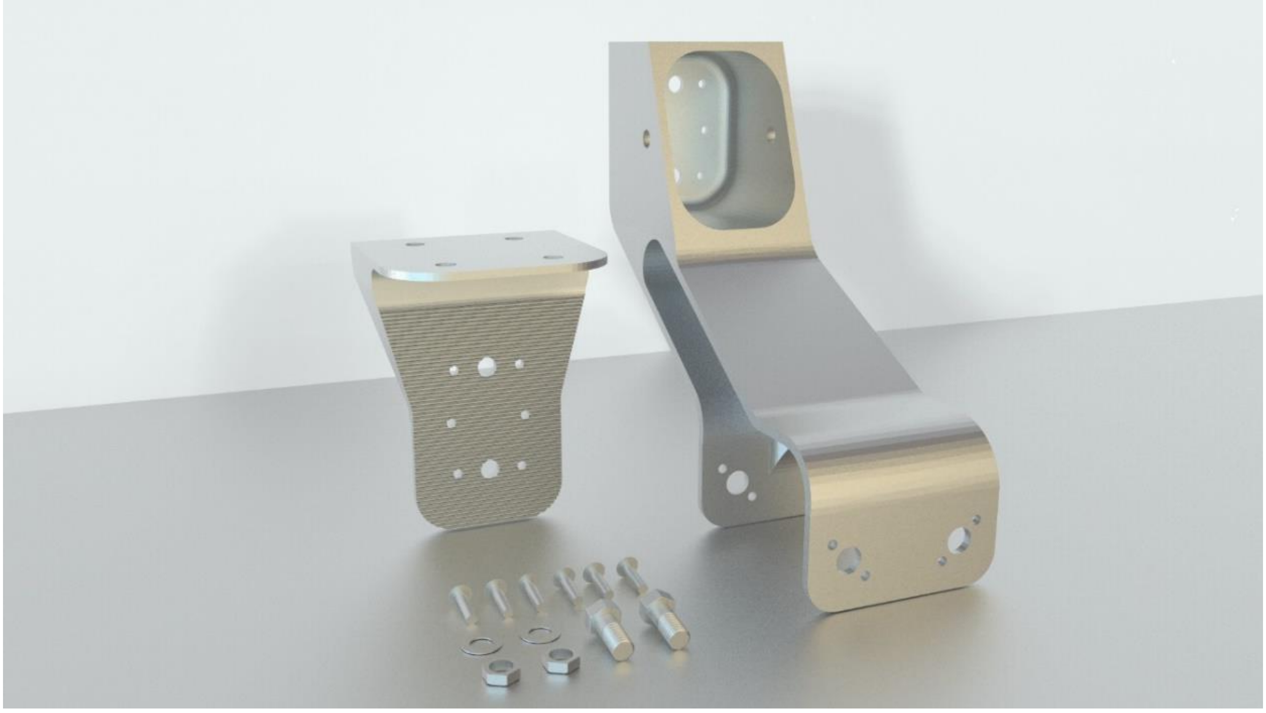
Appendices

Appendix A

Presentation of elements

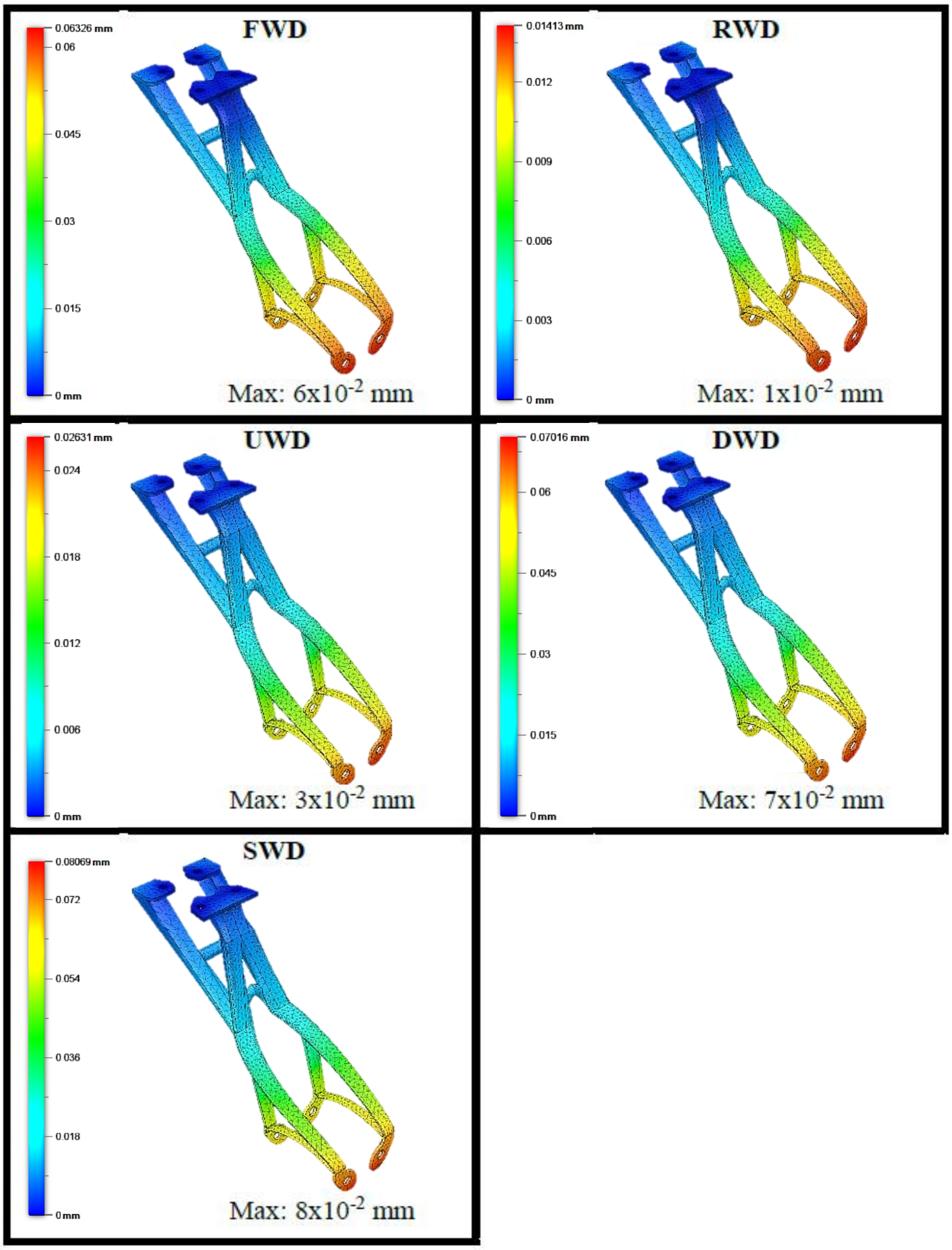
A.1 Presentation of the original bracket with connecting elements



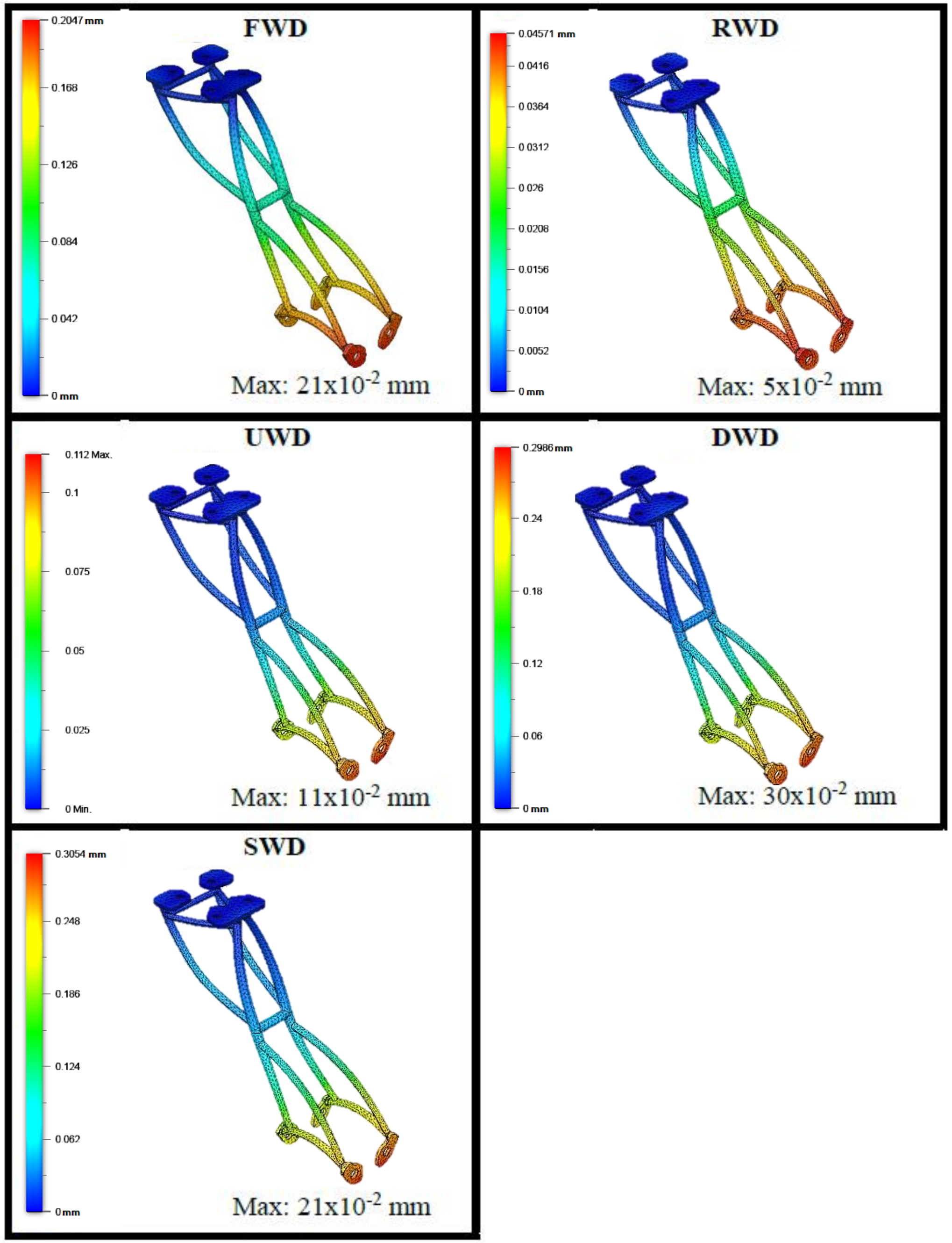
Appendix B

Structural analyses complement

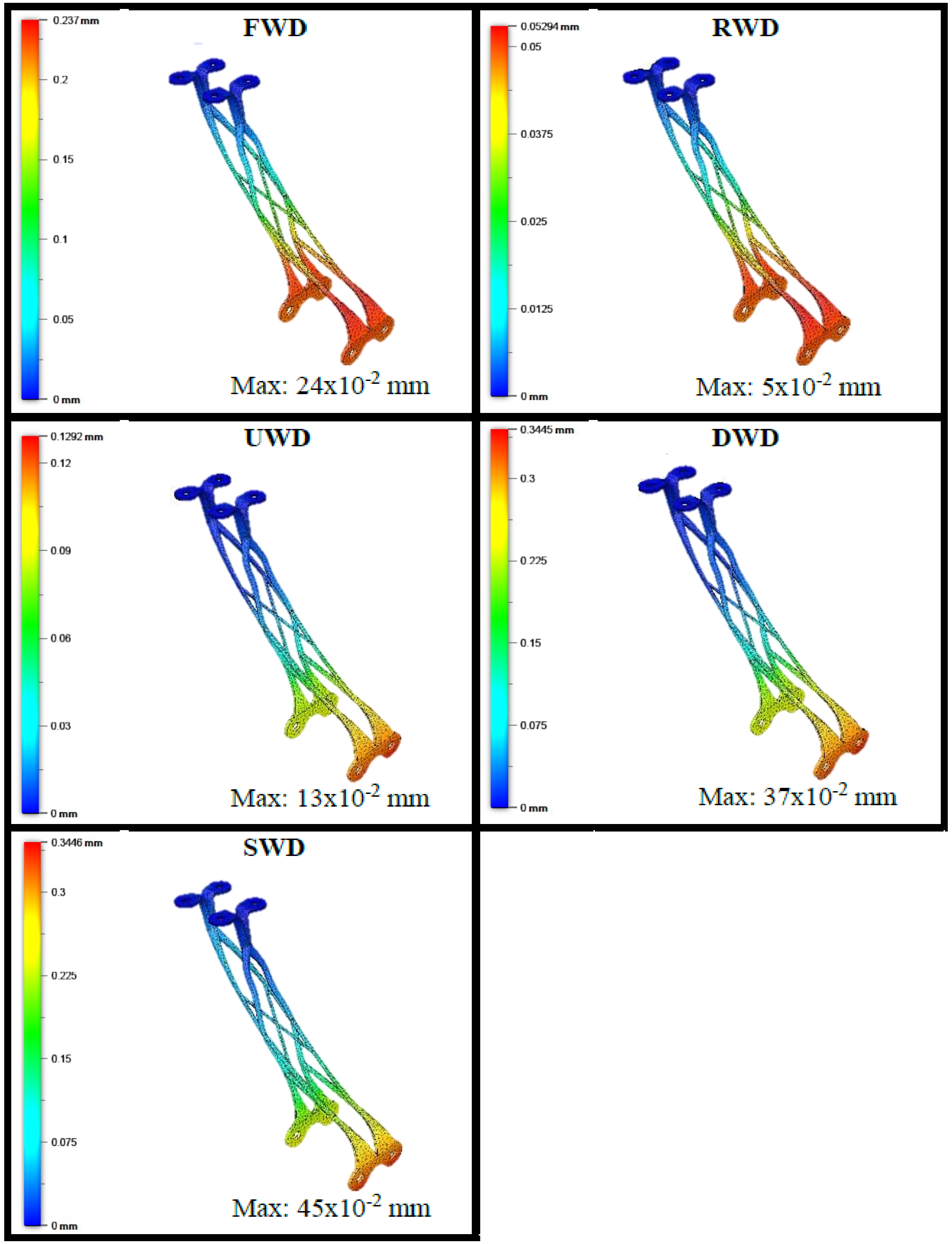
B.1 Displacement for each load case in the bracket V1



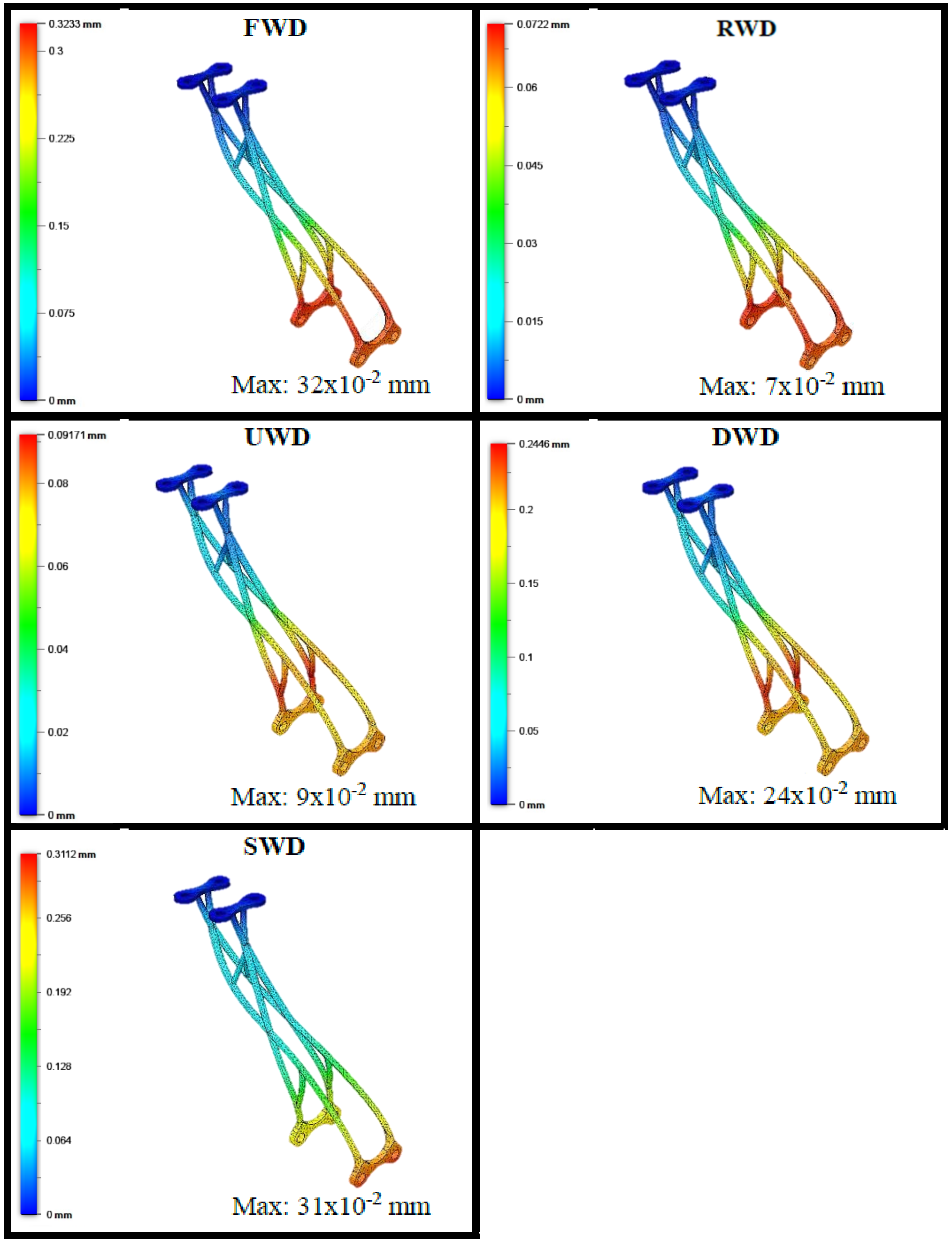
B.2 Displacement for each load case in the bracket V2



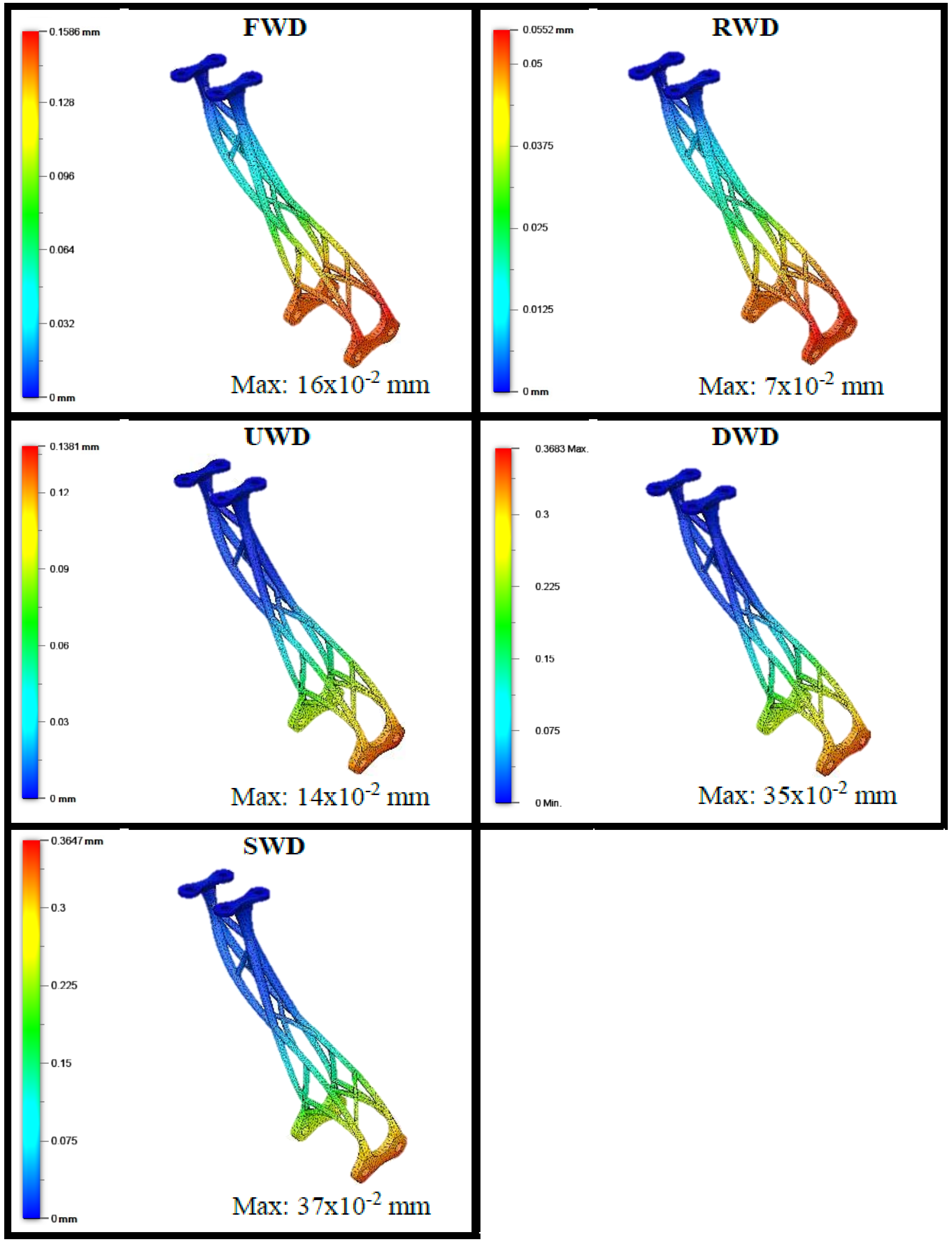
B.3 Displacement for each load case in the bracket V3



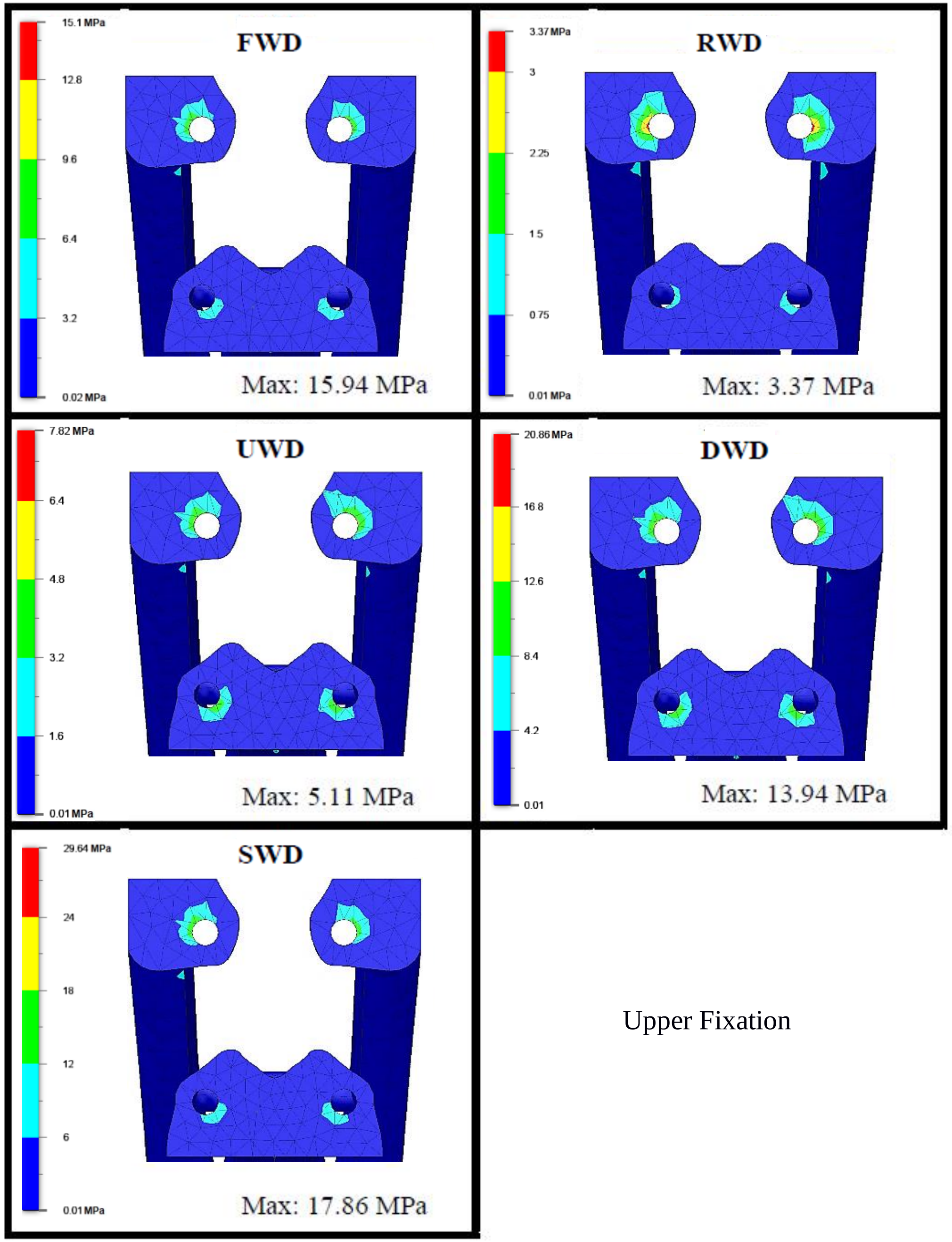
B.4 Displacement for each load case in the bracket V4



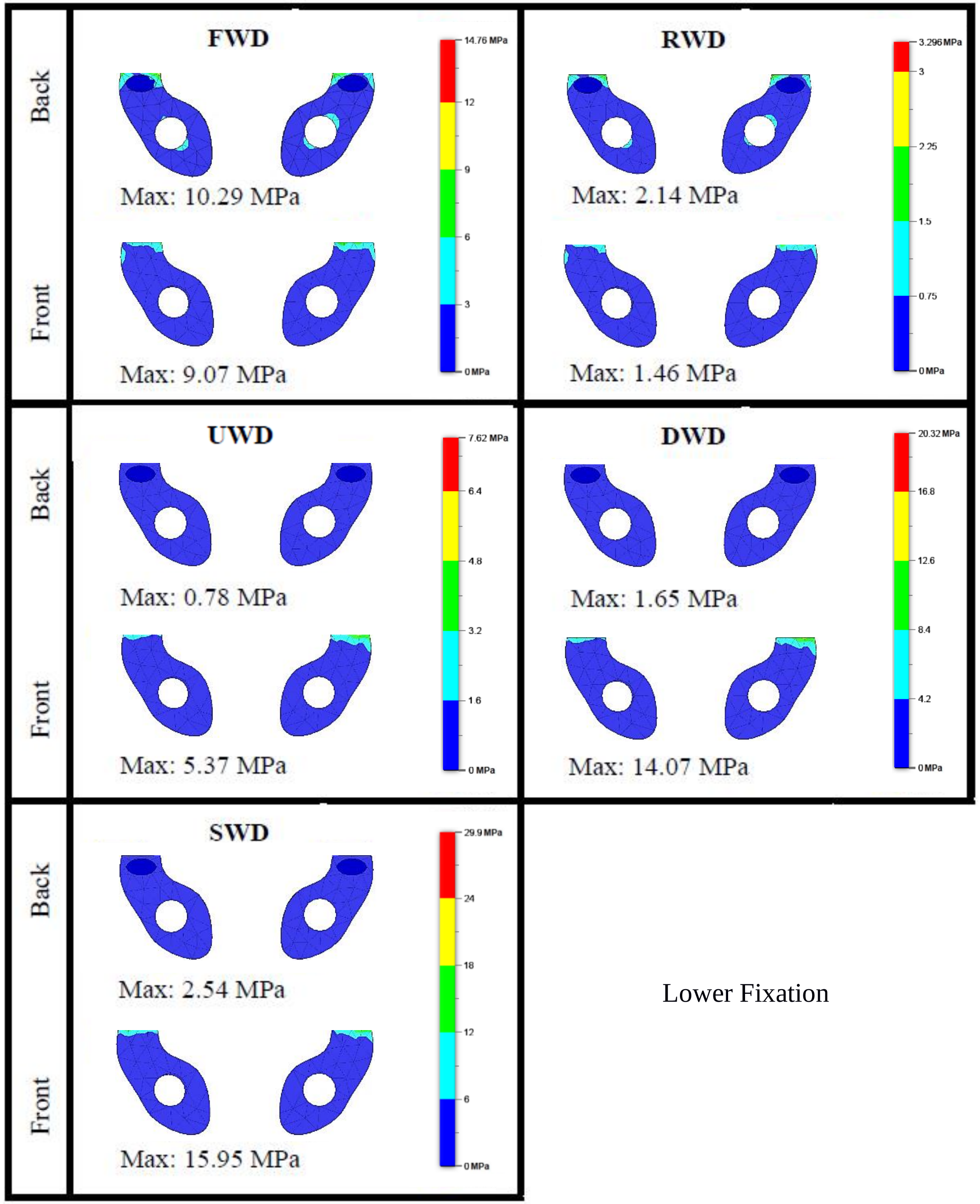
B.5 Displacement for each load case in the bracket V5



B.6 Von Mises stresses in the bracket V1 (Upper Fixation and Lower Fixation regions)

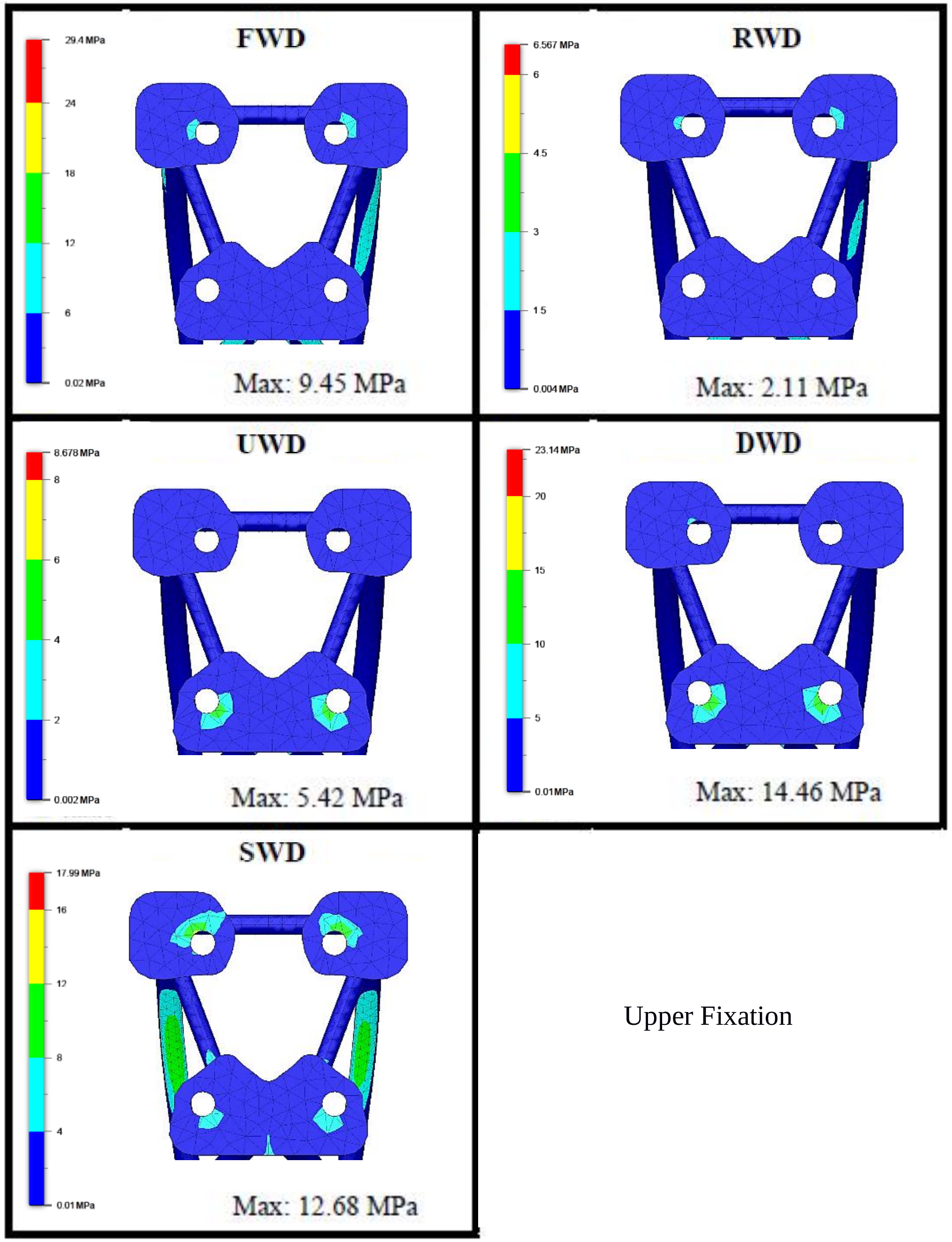


Upper Fixation

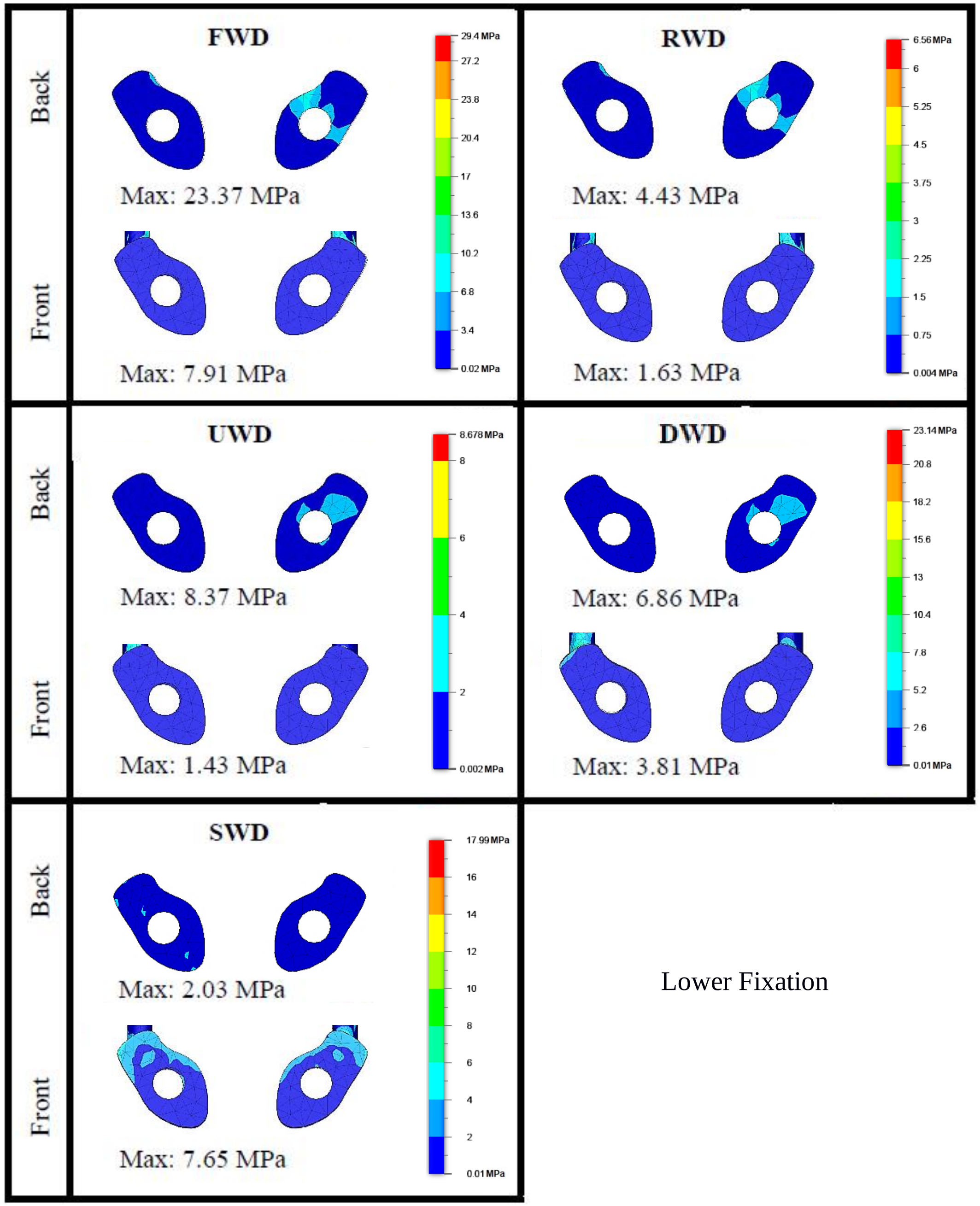


Lower Fixation

B.7 Von Mises stresses in the bracket V2 (Upper Fixation and Lower Fixation regions)

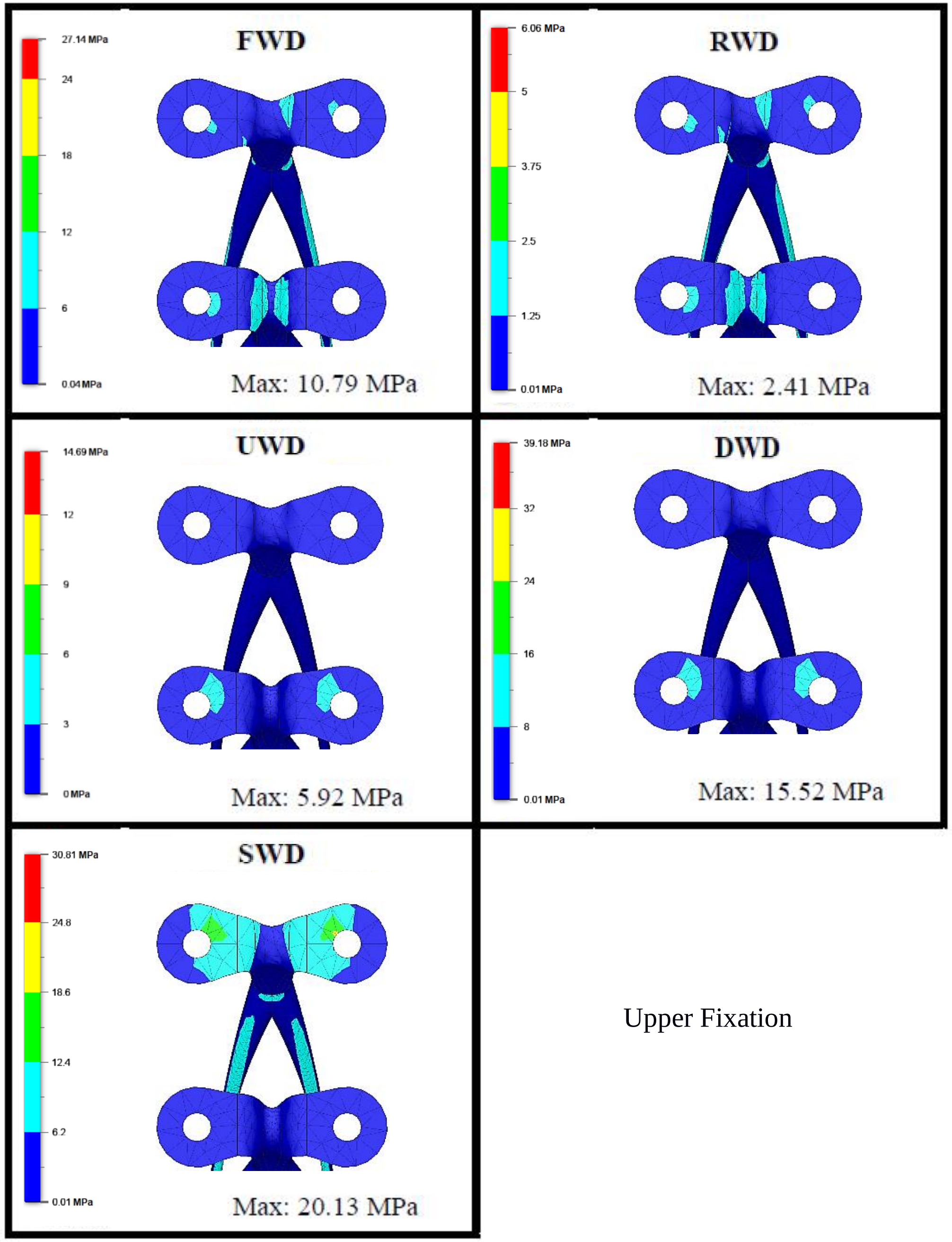


Upper Fixation

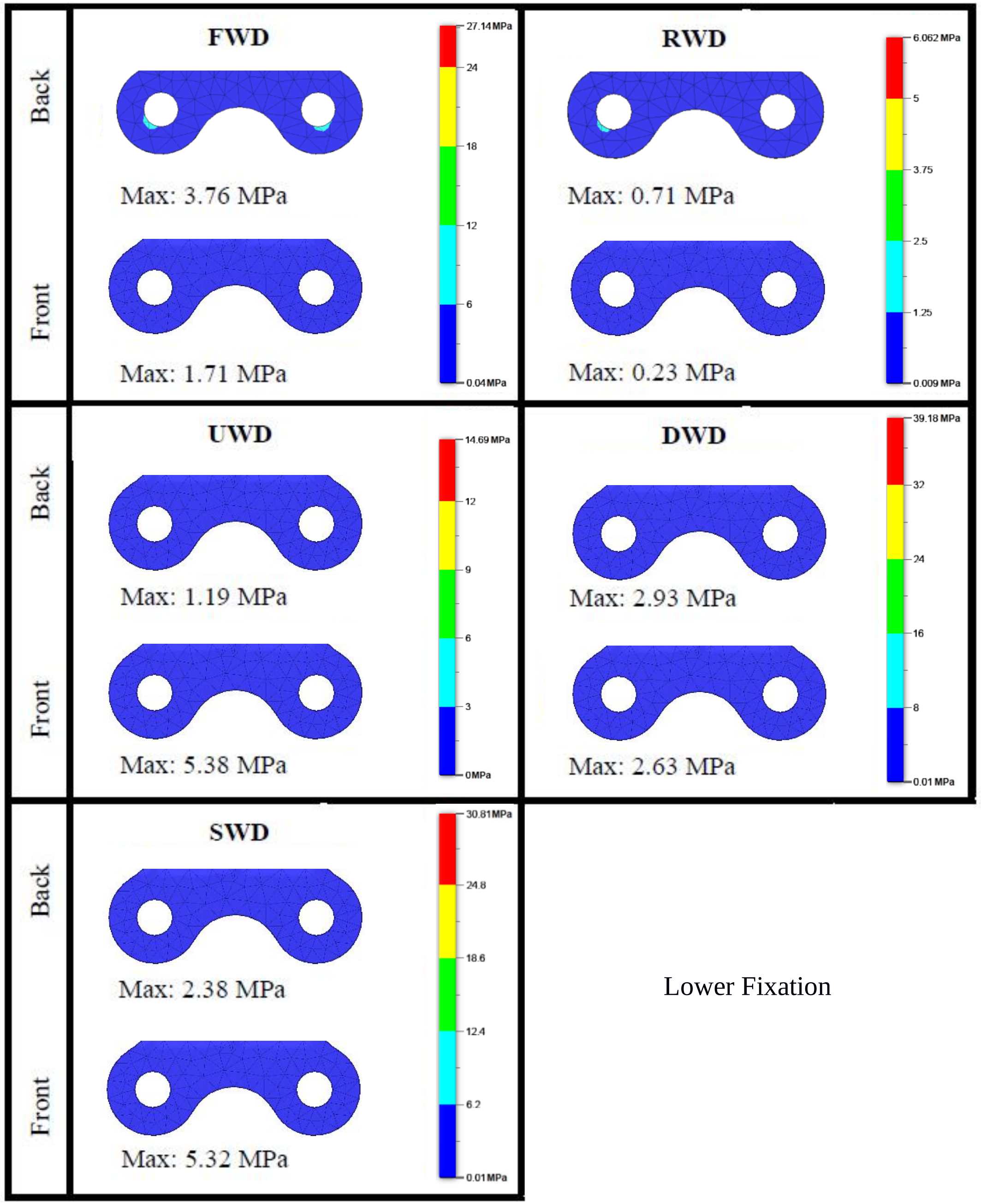


Lower Fixation

B.8 Von Mises stresses in the bracket V3 (Upper Fixation and Lower Fixation regions)

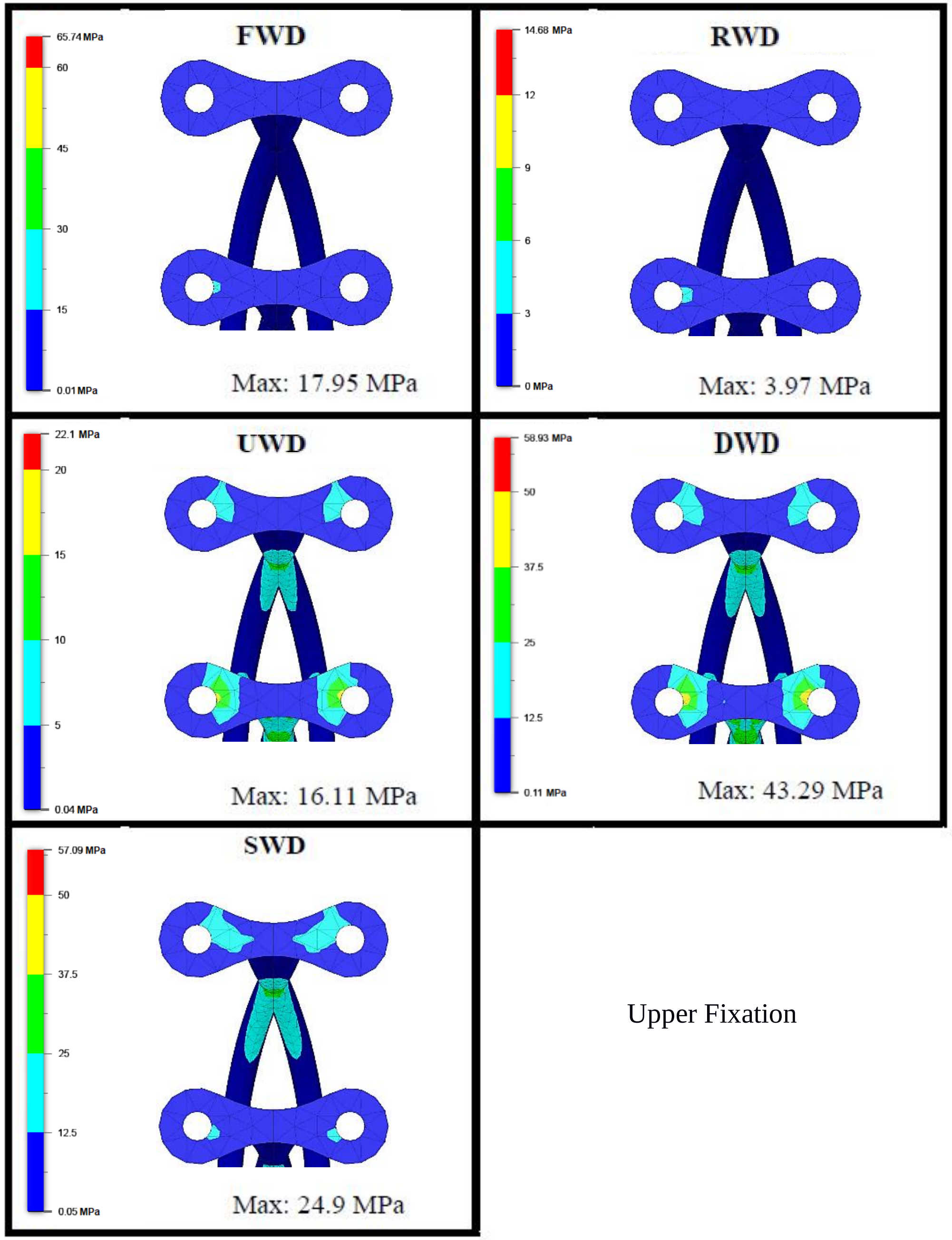


Upper Fixation

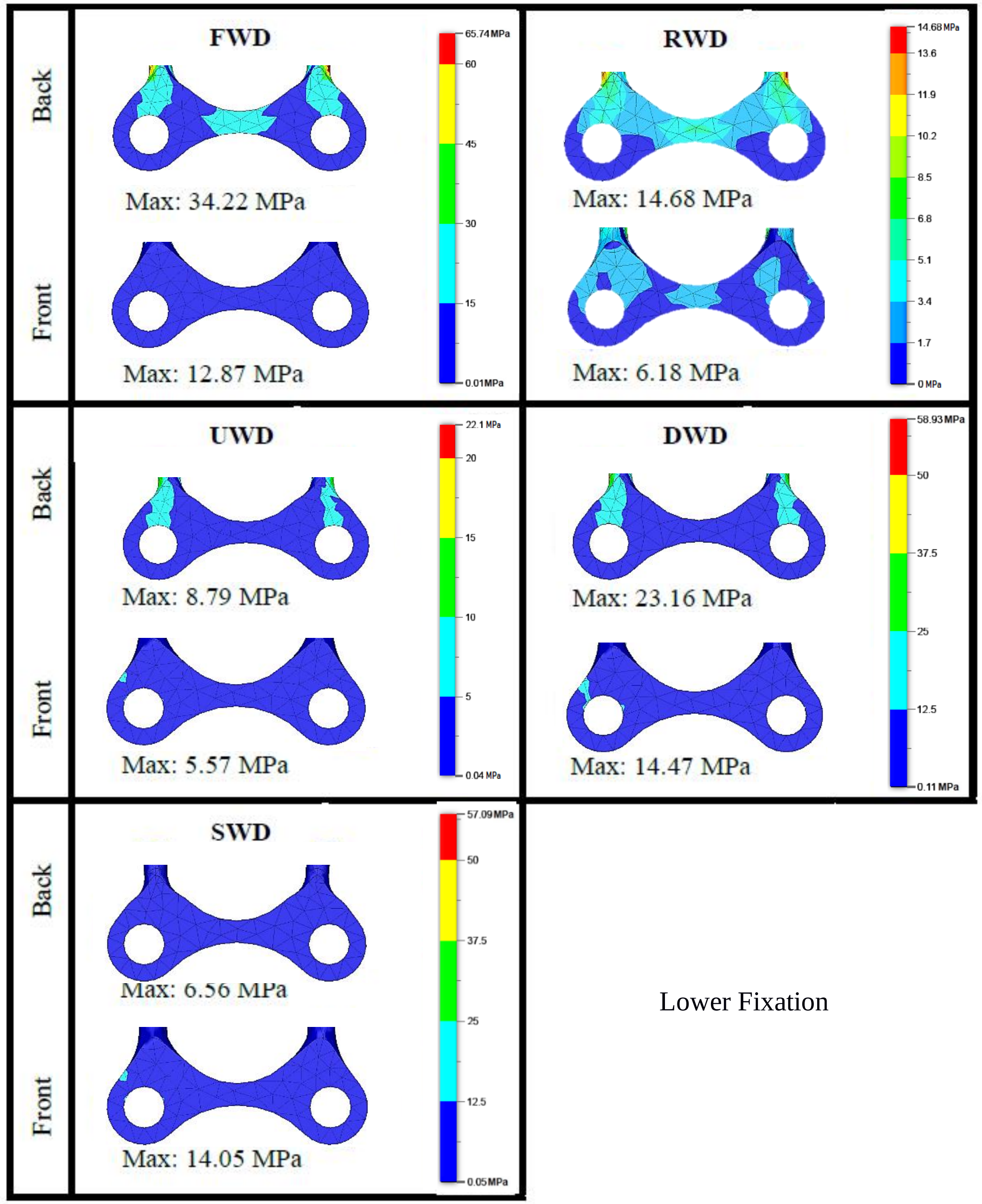


Lower Fixation

B.9 Von Mises stresses in the bracket V4 (Upper Fixation and Lower Fixation regions)

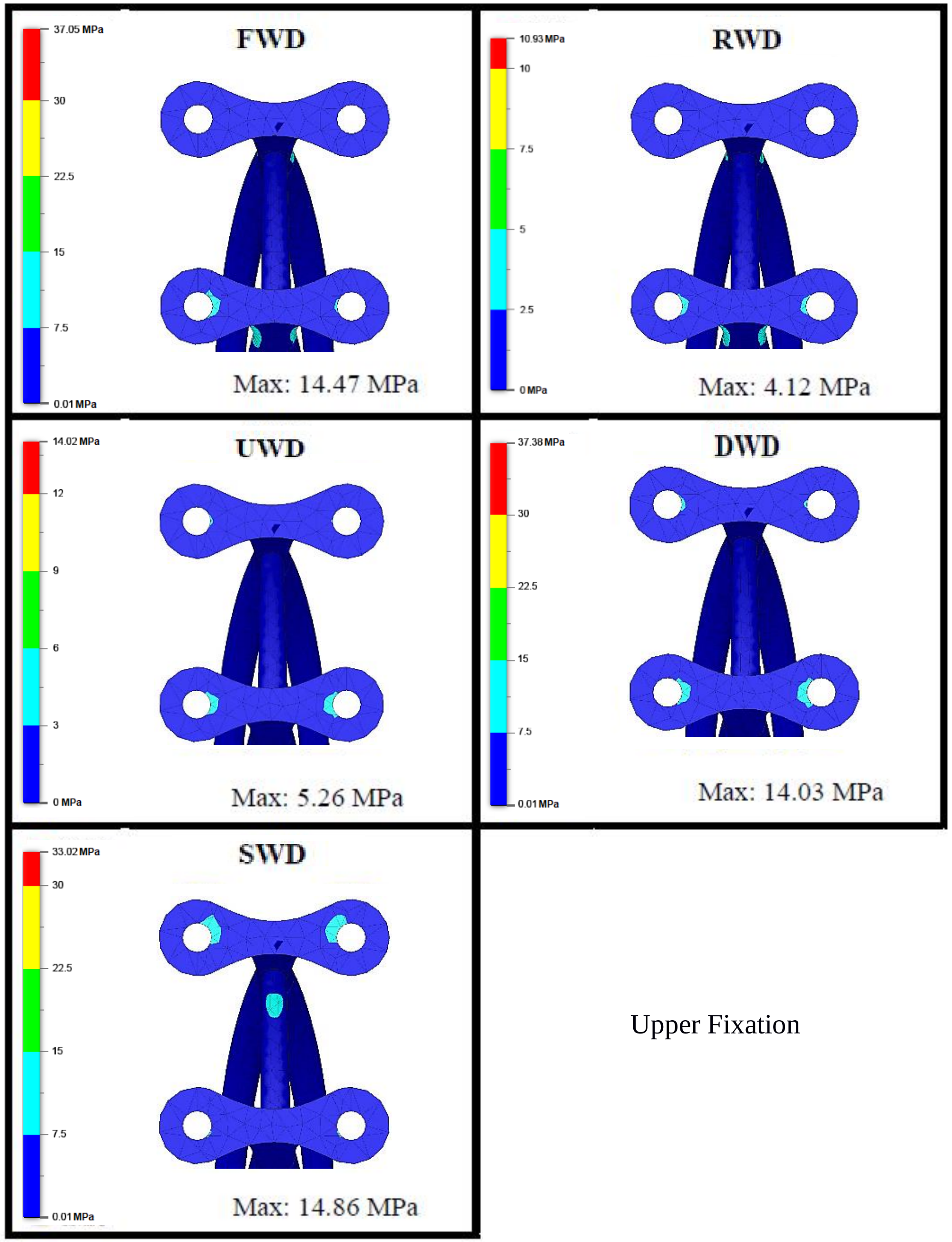


Upper Fixation

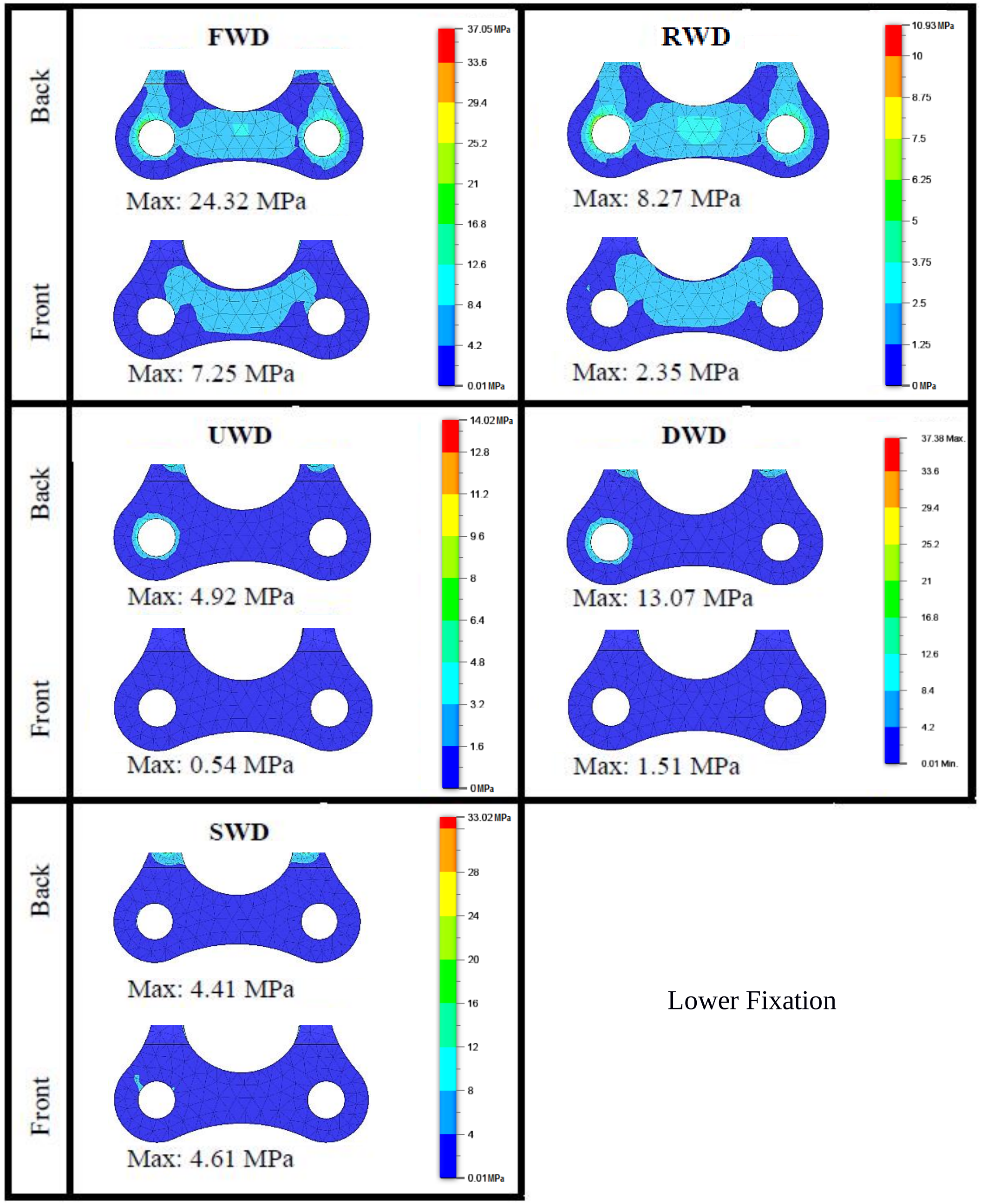


Lower Fixation

B.10 Von Mises stresses in the bracket V5 (Upper Fixation and Lower Fixation regions)



Upper Fixation



Lower Fixation